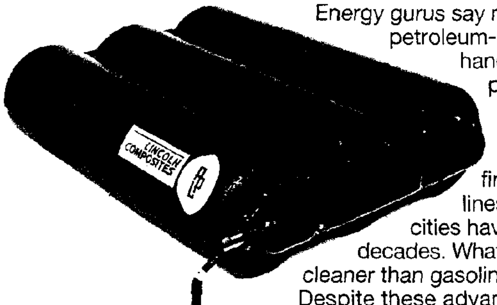
AIR TANKS

COMPOSITE MATERIALS AND IMPACT PROTECTION

Compact Natural Gas Tank

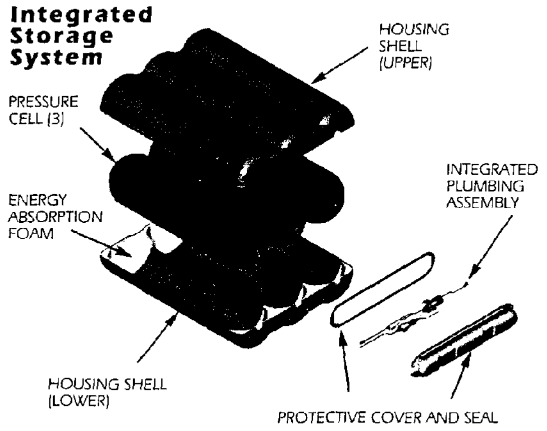


ISS attaches to a car body like conventional gasoline tanks.

Energy gurus say natural gas beats petroleum-based fuels hands down. Supplies are vast and widely distributed. It doesn't need to be refined. And pipelines from wells to cities have existed for decades. What's more, it burns cleaner than gasoline or diesel fuel.

Despite these advantages, the fuel hasn't fired the imagination of car-buyers. And with good reason. To store enough of the gas requires a tank too big for most cars.

Researchers at The Johns Hopkins University Applied Physics Laboratory, in Laurel, Maryland, say their Integrated Storage System (ISS) solves the problem. Made of lightweight composites, it is capable of safely containing gas at 3600 psi. This makes it possible to store enough fuel for most people's travel needs. A demonstration car with ISS is scheduled to debut this fall.



AIR TANKS

COMPOSITE MATERIALS AND IMPACT PROTECTION

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Compressed Air: Its Production, Uses and Applications, Gardner Hiscox, 1909

Compressed air for the purpose of storage and traction by the high-pressure system consists in reservoir capacity due to a collection of steel bottles, connected together in series or by manifolds, whereby the different sections of storage can be cut out from one another.

In the storage system erected at the Twenty-fourth Street, New York City, compressor station there are about 600 bottles. These bottles are all tested to a pressure of 4,500 pounds per square inch, and are used to store air at a pressure of 2,500 pounds per square inch. There is no wear and tear on these storage bottles other than can be made good by painting from time to time. The storage bottles are connected together with proper pipes and valves, and communicate with several charging stands in the car house. The cars can be charged with compressed air at 2,500 pounds pressure in about two or three minutes' time.

The Mannesmann bottles are all tested to a pressure of 4,500 pounds per square inch, and as they are filled with air at a pressure of 2,500 pounds per square inch, there is a factor of safety of about 2. The question is frequently put as to the liability for these tubes to explode. When the tubes are filled with the air at 2,500 pounds per square inch there is no practicable way whereby the pressure can be increased; in fact, the only thing that can happen is for the pressure to decrease.

The recent advance made in steel structural material and weldless tubes has enabled the handling of pressures with absolute safety that were not heretofore thought possible.

These high air pressures mean greater mileage of cars and vehicles, so that compressed-air power has taken a decidedly forward movement for railway and vehicle traction.

THE COMPRESSED-AIR BOTTLE OR RESERVOIR.

As there has been some misapprehension in regard to the strength of the Mannesmann air bottles or reservoirs for high-air pressures as used on street cars and vehicles, we submit some details of tests made on these tubes by the Watson-Stillman Company in presence of many witnesses. A Mannesmann steel tube 5 feet long, 8 inches diameter, and $\frac{1}{4}$ inch thick, which had been in use on a Hardie motor for about two years, carrying air pressure at 2,000 pounds per square inch, was used for the experiments.

The tube was first submitted to a hydraulic pressure of 2,150 pounds, when it was struck several blows with a 14-pound sledge having a 3-foot handle, the sledge being swung from the end of the handle, and weighing, with the handle, 16 pounds. These blows made no impression whatever. At 4,000 pounds the expansion was found to be three-thirty-seconds of an inch. When the pressure was removed, the bottle returned to its original measurement, this pressure being near its limit of elasticity.

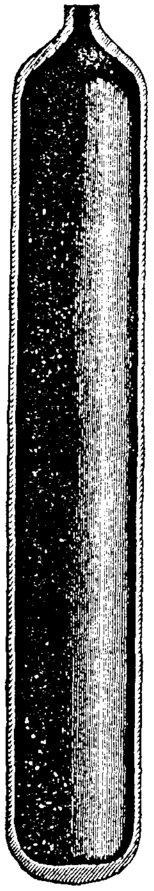


FIG. 120.—AIR BOTTLE.

A second application of pressure was then made up to 5,000 pounds per square inch, at which point the tube began to stretch, and between 5,000 and 6,000 pounds the tube increased one-eighth of an inch circumferentially.

At 6,100 pounds the bottle began to stretch over a small area at a point near its centre, and continued to do so until it was ruptured, at about 6,150 pounds pressure.

The character of the rupture was a mere split in the steel, 18 inches long. No pieces were detached and the fracture was quite regular in its form, showing high ductility in the material and freedom from any liability to project detached pieces in case of a rupture. As the tube tested had been in use in one of the Hardie air motors for a period of two years under a pressure of 2,000 pounds, this indicated that there had been no perceptible deterioration in use, and supported the assertion that the duration of the reservoirs may be considered as indefinite, and that no allowance in estimates of cost of operation need be made for their renewals or repairs.

Other tests have been made of the rupture of these tubes, one of which, 9 inches in diameter, expanded fifteen-sixteenths of an inch before fracture, showing extraordinary ductility, and in all the tests made in Germany and elsewhere upon these tubes no fragments were ever detached and the fracture was always of the same character, a simple longitudinal rent usually near the middle of the tube.

It appears that the tubes did not begin to stretch until a pressure of 5,000 pounds had been reached. Consequently, 4,000 pounds, at which all the tubes are tested, is below the limit of elasticity, and 2,000 pounds, which is the maximum pressure under which the reservoirs are used in the Hardie motors, must be considered to be absolutely safe beyond the possibility of rupture, and even if a rupture should occur, there would be no danger of flying pieces or of any serious accident.

TABLE I. WEIGHT AND VOLUME OF DRY AIR AT SEA-LEVEL PRESSURE AND DIFFERENT TEMPERATURES

Temperature, deg. F.	Weight of 1 cu.ft., in lb.	Volume of 1 lb., in cu.ft.	Temperature, deg. F.	Weight of 1 cu.ft., in lb.	Volume of 1 lb., in cu.ft.
0	.0864	11.582	110	.0698	14.345
10	.0846	11.834	120	.0686	14.596
20	.0828	12.085	130	.0674	14.847
30	.0811	12.336	140	.0663	15.098
32	.0807	12.386	150	.0652	15.350
40	.0795	12.587	160	.0641	15.601
50	.0780	12.838	170	.0631	15.852
60	.0764	13.089	180	.0621	16.103
62	.0761	13.141	190	.0612	16.354
70	.0750	13.340	200	.0603	16.605
80	.0736	13.592	210	.0593	16.856
90	.0723	13.843	212	.0591	16.907
100	.0710	14.094			

TABLE II.—WEIGHT OF AIR AT VARIOUS TEMPERATURES AND PRESSURES

(Sea-level pressure = 14.7 lb. abs.)

Temperature of Air, Deg. F.	Gage Pressure, Lb.																		
	0	5	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	175	200
	Weight, Lb. per Cu.ft.																		
−10	.0882	.1184	.1485	.2090	.2685	.3283	.3880	.4478	.5076	.5674	.6272	.687	.747	.807	.868	.928	.989	1.139	1.288
0	.0864	.1160	.1455	.2040	.2630	.3215	.3800	.4385	.4970	.5555	.6140	.672	.731	.790	.849	.908	.968	1.114	1.260
10	.0846	.1136	1425	.1995	.2568	.3145	.3720	.4292	.4865	.5433	.6006	.658	.716	.774	.832	.889	.947	1.090	1.233
20	.0828	.1112	.1395	.1955	.2516	.3071	.3645	.4205	.4770	.5330	.5890	.645	.701	.757	.813	.869	.927	1.067	1.208
30	.0811	.1088	.1366	.1916	.2465	.3015	.3570	.4121	.4672	.5221	.5771	.632	.687	.742	.797	.852	.908	1.046	1.184
40	.0795	.1067	.1338	.1876	.2415	.2954	.3503	.4038	.4576	.5114	.5652	.619	.673	.727	.781	.835	.890	1.025	1.161
50	.0780	.1045	.1310	.1839	.2367	.2905	.3432	.3960	.4487	.5014	.5541	.607	.660	.713	.766	.819	.873	1.006	1.139
60	.0764	.1025	.1283	.1803	.2323	.2840	.3562	.3882	.4402	.4927	.5447	.596	.649	.700	.752	.804	.856	.988	1.116
70	.0750	.1005	.1260	.1770	.2280	.2791	.3302	.3808	.4316	.4824	.5332	.584	.635	.686	.737	.788	.839	.967	1.095
80	.0736	.0988	.1239	.1738	.2237	.2739	.3242	.3738	.4234	.4729	.5224	.572	.622	.673	.723	.774	.824	.949	1.074
90	.0723	.0970	.1218	.1707	.2195	.2688	.3182	.3670	.4154	.4639	.5122	.561	.611	.660	.709	.759	.809	.932	1.054
100	.0710	.0954	.1197	.1676	.2155	.2638	.3122	.3602	.4079	.4555	.5033	.551	.599	.648	.696	.745	.794	.914	1.035
110	.0698	.0937	.1176	.1645	.2115	.2593	.3070	.3542	.4011	.4481	.4950	.542	.589	.637	.685	.732	.780	.899	1.017
120	.0686	.0921	.1155	.1618	.2080	.2549	.3018	.3481	.3944	.4403	.4866	.533	.579	.626	.673	.720	.767	.884	1.001
130	.0674	.0905	.1135	.1590	.2045	.2505	.2966	.3446	.3924	.4296	.4770	.524	.570	.616	.662	.708	.754	.869	.984
140	.0663	.0889	.1115	.1565	.2015	.2465	.2915	.3364	.3813	.4262	.4711	.516	.561	.606	.651	.696	.742	.855	.968
150	.0652	.0874	.1096	.1541	.1985	.2425	.2865	.3308	.3751	.4193	.4636	.508	.552	.596	.640	.685	.730	.841	.953
175	.0626	.0840	.1054	.1482	.1910	.2335	.2755	.3181	.3607	.4033	.4450	.488	.531	.573	.616	.658	.701	.808	.914
200	.0603	.0809	.1014	.1427	.1840	.2248	.2655	.3054	.3473	.3882	.4291	.470	.511	.552	.592	.633	.674	.776	.879
225	.0581	.0779	.0976	.1373	.1770	.2163	.2555	.2949	.3344	.3738	.4129	.452	.491	.531	.570	.609	.649	.747	.846
250	.0560	.0751	.0941	.1323	.1705	.2085	.2466	.2845	.3223	.3602	.3981	.436	.474	.513	.551	.589	.627	.722	.817
300	.0523	.0707	.0881	.1237	.1592	.1945	.2300	.2654	.3008	.3362	.3716	.407	.442	.478	.513	.549	.585	.673	.762
350	.0491	.0658	.0825	.1160	.1495	.1828	.2160	.2492	.2824	.3156	.3488	.382	.415	.449	.482	.516	.549	.632	.715
400	.0463	.0621	.0779	.1090	.1405	.1720	.2035	.2348	.2661	.2974	.3287	.360	.391	.423	.454	.486	.517	.596	.674
450	.0437	.0586	.0735	.1033	.1330	.1628	.1925	.2220	.2515	.2810	.3105	.340	.369	.399	.429	.458	.488	.562	.637
500	.0414	.0555	.0696	.0978	.1260	.1540	.1820	.2100	.2380	.2660	.2940	.322	.351	.379	.407	.435	.463	.534	.604

Compressed Air Plant
Robert Peele

R.H. Warring, 42-46.

PNEUMATIC ENGINEERING CALCULATIONS

Strength of Receivers

(66) The following formula is applicable for determining the minimum wall thickness for cylindrical receiver shells.

$$t = \frac{PD}{2(S - 0.5P)} + c \quad \text{inches}$$

$$= \frac{PR}{S - 0.5P} + c \quad \text{inches}$$

where P = maximum working pressure, psig
D = inside diameter, inches
R = inside radius, inches
S = maximum permissible material stress at maximum service temperature, psi
c = corrosion allowance, normally taken as 0.03 in

Example: a receiver is 12 in diameter and is to take a maximum working pressure of 200 psig. Find the minimum wall thickness if maximum permissible material stress of 15 000 psi is not to be exceeded.

$$t = \frac{200 \times 12}{2(15\,000 - 0.5 \times 200)} + 0.03$$

$$= 0.0805 \text{ in} + 0.03$$

$$0.1105 \text{ inches}$$

(67) Dished ends:

A minimum material thickness for dished ends fabricated from sheet or plate is given by the formula

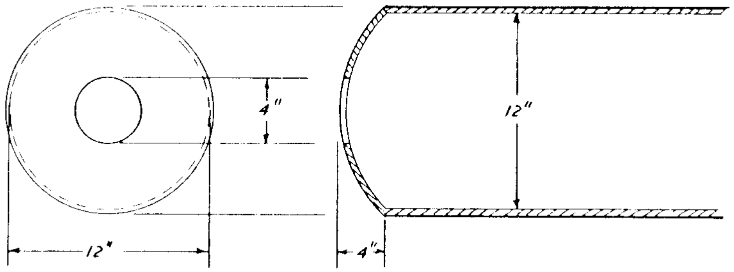
$$t_e = \frac{CPD}{2S} + c$$

where C = shape factor (see Table)

SHAPE FACTORS (Plain ends and non-reinforced openings)

H/D *		0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6
Plain End		1.3	1.05	0.8	0.7	0.6	0.55	0.55	0.55	0.55
With opening of diameter d	$d/\sqrt{D}$ 1	1.5	1.2	1.05	0.9	0.9	0.85	0.8	0.8	0.8
	2	1.85	1.6	1.45	1.3	1.25	1.2	1.1	1.1	1.1
	3	2.3	2.05	1.9	1.75	1.65	1.6	1.5	1.45	1.45
	4	2.8	2.5	2.3	2.15	2.05	1.95	1.9	1.85	1.8
	5	3.25	2.95	2.7	2.5	2.35	2.25	2.2	2.15	2.1

* H = height of drumhead D = diameter of end



Example: receiver diameter is 12 in and the depth of the dished end is 4 in. A 4 in unreinforced cut-out is incorporated. Find the minimum material thickness required. Maximum working pressure 200 psig and S_{max} = 15 000 psi.

$H/D = 4/12 = 0.33$

$d/\sqrt{D} = 4/\sqrt{12} = 1.16$

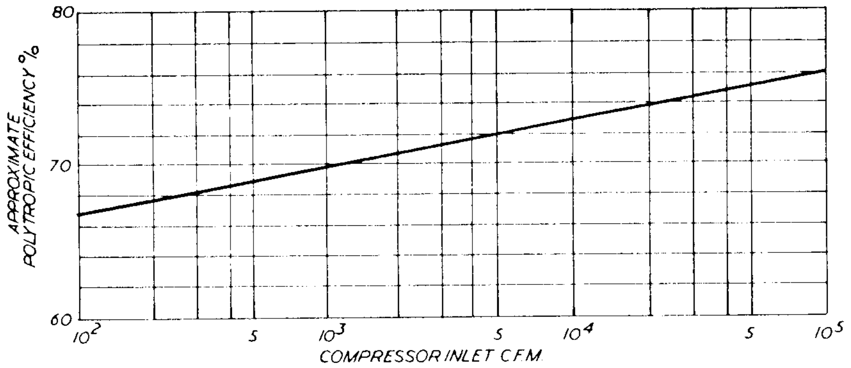
From Table above a conservative value for the shape factor is 1.1

$$\text{Thus } t = \frac{1.1 \times 200 \times 12}{2 \times 15\,000} + [illegible] \quad 0.3$$

$$= 0.088 + 0.03$$

$$= 0.118 \text{ inches}$$

Note: cut out diameter should not exceed a certain maximum value dependent on the receiver diameter and wall thickness - see Chart 2.


APPROXIMATE POLYTROPIC EFFICIENCY %
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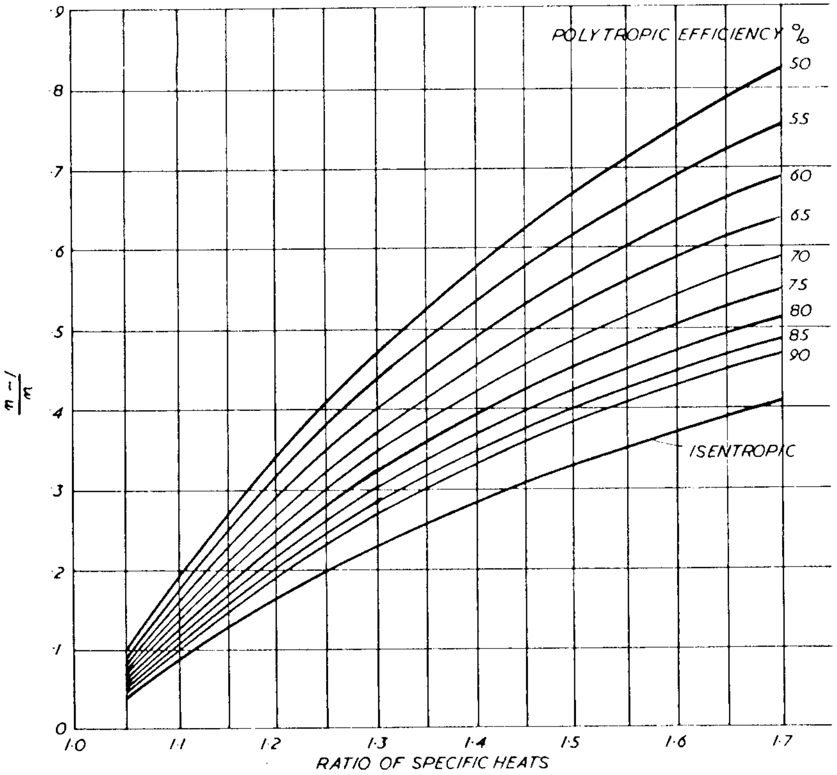
10^3
5
10^4
5
10^5
COMPRESSOR INLET C.F.M.


$\frac{n-1}{n}$
·9
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·7
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·4
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·2
·1
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1·3
1·4
1·5
1·6
1·7
RATIO OF SPECIFIC HEATS
POLYTROPIC EFFICIENCY %
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90
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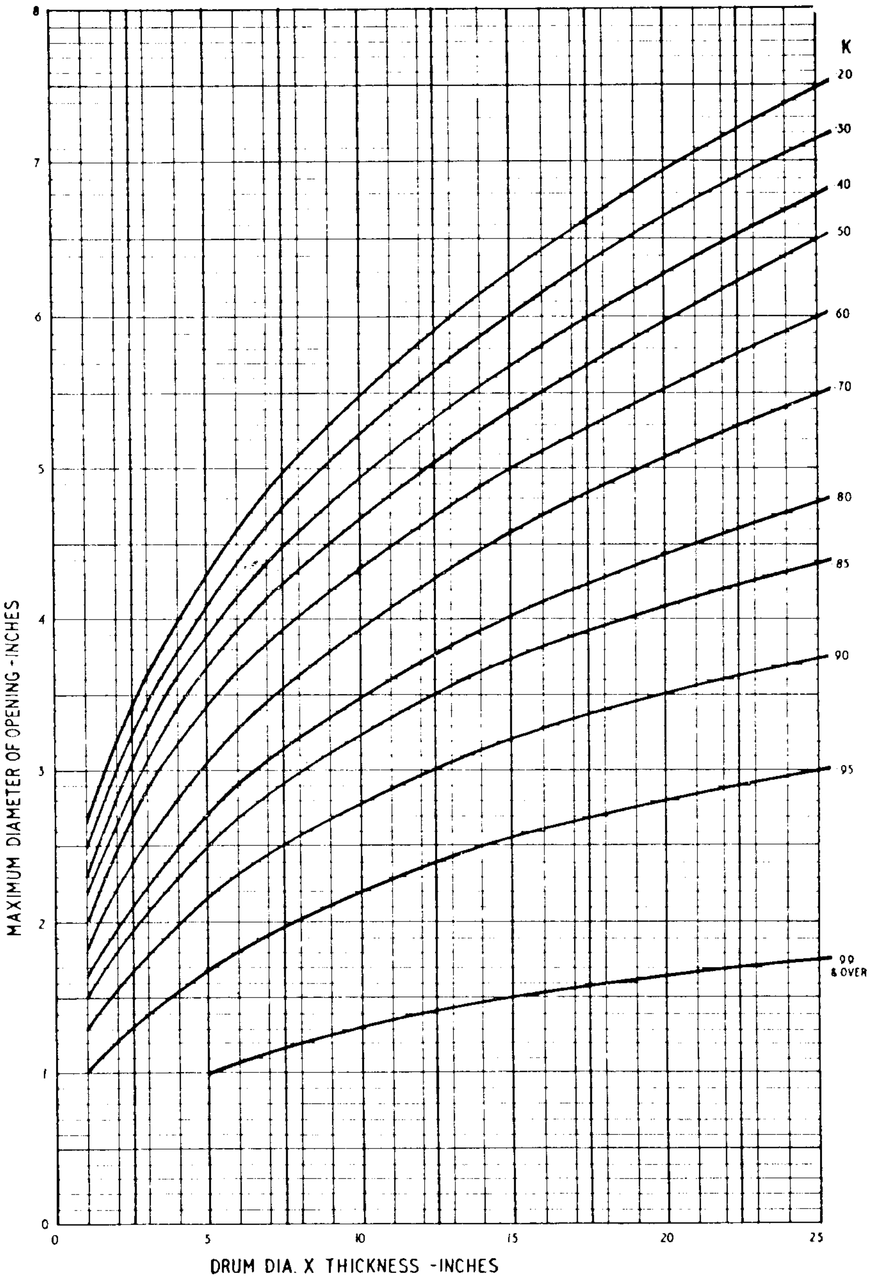
MAXIMUM DIAMETER OF OPENING - INCHES
8
7
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5
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3
2
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0
0
5
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15
20
25
DRUM DIA. X THICKNESS - INCHES
K
·20
·30
·40
·50
·60
·70
·80
·85
·90
·95
·99 & OVER

(68) Maximum permissible material stress for Welded Construction:

Maximum permissible material stress should be estimated on the following basis –

$$S_{max} = \frac{\text{yield point}}{\text{factor of safety}} \times Z$$

where Z = weld factor.

Recommended minimum factors of safety – 1.6 for pressure vessel steels
2.0 for semi-killed and killed structural steels

Recommended weld factors – Z = 0.8 for general use
Z = 0.9 with X-ray control

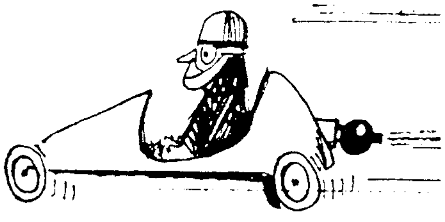
Example: Upper yield point of BS 1501 Grade 23 steel (pressure vessel steel) is 29 300 psi. Determine a value for maximum permissible stress for this material used for welded pressure vessel construction. Assume no flying X-ray control available.

$$S_{max} = \frac{29\,300}{1.6} \times 0.8$$
$$= 16\,500 \text{ psi}$$

Civilian role sought for pneumatic batteries

A PNEUMATIC battery the size of a cricket ball can store enough energy in the form of compressed gas to accelerate itself to the speed of sound. In electrical terms, that is enough energy to power a 0·3 watt torch for seven hours.

The batteries, produced by Hymatic Engineering in Britain, are used by the armed forces. Now the company is looking for a mass market in civilian applications, such as powering release and control mechanisms in helicopters, or in chemical process plants, where an electric spark would be disastrous.



There are two main ingredients to storing energy pneumatically: a gas that can be highly compressed—one of the noble gases—and a leak-tight container. The containers need to hold pressures 500 times greater than that in a car tyre for durations of 15 years or more.

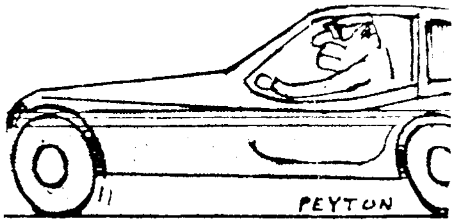
Typically, air is used in the range of pressures up to 415 × 10^5 bar, a helium air mix is used between 415 × 10^5 and 6896 × 10^5 bar, and helium alone can be compressed to 11 724 × 10^5 bar. The energy of this stored gas can be tapped in one go, or allowed to trickle out in the same fashion as charge from a battery.

At pressures of 6896 × 10^5 bar, air can be as dense as wood. The bottles must be machined from solid metal for strength, and must be of the right material; impurities make some types of steels slightly porous, and the gas would leak away.

Moreover, materials used for seals in normal pneumatic devices are useless. Specialised sealing techniques, such as electron beam welding or a high precision plug is machined to provide a metal to metal seal, are needed.

An operator controls production of the pneumatic store by keying in the store's properties to a computer. The company's flexible manufacturing system then turns out the desired shape. The optimum shape for storing energy is a sphere, but all sorts of other shapes are possible such as tubes and cones, or a combination that fits the available space in equipment.

Rechargable pneumatic energy stores were first developed in the 1950s. Now disposable pneumatic stores appear in a range of military applications. For example, they kick a gyroscope into action or control the wings or fins of a projectile. In the latter application, gas is released from the battery, through a valve that regulates pressure, to servos. In turn, pistons move the fins. For the armed forces, pneumatic equipment has one big advantage over electronics; it is immune to electromagnetic interference of the sort that would follow a nuclear explosion.



The cost of a small battery is about £100. But Hymatic Engineering believes that the cost could drop to between £10 and £15 if it can break into a mass market. □

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Aerospace Congress & Exposition
Anaheim, California
October 5-8, 1981

Commercial Filament Wound Pressure Vessels for Military and Aerospace Applications

SAE Technical Paper Series

Edgar E. Morris
STRUCTURAL COMPOSITES INDUSTRIES, INC.
325 ENTERPRISE PLACE, POMONA, CA 91768, (714) 594-7777

IN THE 1960s, LIGHT-WEIGHT HIGH-strength pressure vessels were needed for space, missile, and military aircraft and underwater systems. Programs were sponsored by NASA-Lewis Research Center and the Air Force Materials Laboratory to design, develop, fabricate and evaluate composite tanks made by overwrapping thin metal liners with continuous high strength fibers embedded in resins based on technology developed for solid rocket motor cases. The resulting pressure vessels were 20 to 50 percent lighter than homogeneous metal vessels and offered other advantages, including enhanced safety with leakage mode-of-final-failure instead of catastrophic rupture.

Then, in the early 1970s, NASA was faced with the demand to help commercialize government-sponsored technology. In response, the Johnson Spacecraft Center awarded contracts for the development, pilot manufacture and service test of an improved light-weight commercial fireman's breathing system. Under this program, SCI fabricated aluminum cylinders fully reinforced by S-glass filaments. These 4000 psig operating pressure composite tanks were used in field tests by the Fire Departments of New York City, Los Angeles and Houston with excellent results. Similar fireman's breathing system composite cylinders with 2216 psig operating pressure have been commercially produced by SCI for Mine Safety Appliances Company since 1976, and the 50,000th unit was recently delivered.

In 1974, the Boeing Commercial

ABSTRACT

Light weight, low cost, composite pressure vessels, fabricated by overwrapping thin metal liners with continuous high strength fibers embedded in resins, have been developed as a result of transferring aerospace technology to commercial products. Because the resulting filament wound tanks offer up to 50% reduction in weight and other advantages compared to homogeneous metal vessels, they have been successful in numerous commercial applications. With their advanced technology but lower cost, composite tanks are perfect for military and aerospace applications - as evidenced by the recent selection of commercial filament wound cylinders for the Manned Maneuvering Unit thruster for Space Shuttle astronauts.

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Airplane Company decided to use composite reinforced cylinders for escape slide inflation to meet weight objectives on their long range 747 Aircraft. SCI developed a Kevlar/aluminum tank for this application and in 1976 received the first Department of Transportation authorization for routine commercial use of a composite reinforced cylinder.

Since then many other filament wound tanks have been developed for commercial use. So successful has this technology transfer from government to commercial applications been that now commercial composite pressure vessels are being chosen for military and aerospace applications. For example, NASA selected commercial filament wound tanks, developed by SCI in 1979, for the Manned Maneuvering Unit (MMU) of Space Shuttle.

This paper describes composite pressure vessels and explains their development, fabrication, advantages and uses.

DESCRIPTION

Composite pressure vessels are usually cylinders or spheres. Sizes of currently available composite cylinders range in volume from approximately 45 to over 10,000 cubic inches with diameters of 3 to over 20 inches. Operating pressures are normally from 2000 to 4500 psig; burst pressures must be three times operating pressure to comply with government regulations for commercial composite cylinders. Aerospace spheres produced have ranged in volume from 32 to over 27,000 cubic inches with diameters from 4 to over 38 inches and operating pressures of 2000 to 4500 psig with burst pressure 1.5 to 3 times operating pressure.

Presently, commercial tanks are cylinders made from thin metal liners overwrapped with continuous high strength fibers embedded in resins. The liner's purpose is to prevent leakage and provide a boss for the valve. However, it also serves as a filament winding mandrel during production and shares the pressure load during service. The usual liner material is seamless aluminum, but steel and other materials are also utilized. A seamless liner without welds or joints is desirable to minimize potential failures from fatigue or mishandling; however, welded liners are used for special applications. E-glass (240,000 psi minimum tensile strength), S-glass (350,000 psi minimum tensile strength) and Kevlar-49 (340,000 psi minimum tensile strength) fibers are usually used for overwrapping; however, the cost of Kevlar (~ \$10/lb) often limits its use to aircraft, military and aerospace applications. Although graphite fibers are a possibility, there are no known graphite units in commercial production - largely because of the high cost of graphite fibers without potential for significant additional weight saving. The glass or Kevlar fibers, in a resin system that is usually epoxy with either amine or anhydride curing, are filament wound over the liner.

Some future commercial tanks will certainly be composite spheres. They can directly replace metal spheres in existing pneumatic systems or be designed for new systems where the available envelope dictates a spherical shape.

DEVELOPMENT

The origin of commercial composite pressure vessels lies in the aerospace/defense industry fabrication of filament wound solid rocket motor cases. These single-use devices have to contain propellant combustion gases at high pressure (1000-1500 psi) and temperature (3000-5000°F) for short periods (~150 sec) and be as light weight as possible. Their liners are usually a rubber insulation material. The filament wound motor cases have polar bosses at both ends to accommodate an ignitor and a nozzle. The transfer of this technology to commercial pressure vessel products required the development of metal liners for long term storage, composite wrappings to carry most of the structural load and environmentally-resistant resin systems for the wrapped fibers to survive a variety of conditions for approximately 20 years of repeated use. To reduce cost and weight, the number of bosses was reduced from two to one for most applications; the single boss was converted to an end fitting for a valve or regulator and made part of the liner. Thus, there is no metal-to-composite joint. Since the pressure vessel loading on the composite structure is almost entirely tensile (without bending or shear), the composite cylinder is an ideal use of high strength fibers.

However, the composite pressure vessel had not been proven in commercial applications. High pressure gases (usually at 2000-4500 psi) are considered dangerous commodities, and their transportation in interstate commerce makes their containers subject to the regulations of the Department of Transportation. Steel cylinder regulations (called specifications), which generally reflect the codification of the existing practice when they were written many years ago, are well documented, but there are no specifications for composite cylinders. Thus, their uses are authorized by "Exemptions" to the specifications. To demonstrate that the safety of a composite cylinder is equivalent to a steel cylinder, extensive qualification tests are required for each type of composite cylinder. Since receiving the first such exemption in 1976, SCI has obtained others as needed for new pressure vessel models.

FABRICATION

LINER - Aluminum liners for composite cylinders can be fabricated by:

- Impact Extrusion
  This is a two step process. First is an impact to make an open cup, and second is an impact on the open end of the cup to close it and form the boss.
- Deep Draw and Spin
  This is a multi-step operation, as shown in Fig. 1, with intermediate anneals. The final step is spin closing without a mandrel. Although more expensive than impact extrusion, this process permits thin wall liners with close tolerances on thicknesses.

Resulting aluminum liners (6061 or 6351) are heat treated to the T6 condition and then machined to shape the boss and provide threads for the valve.

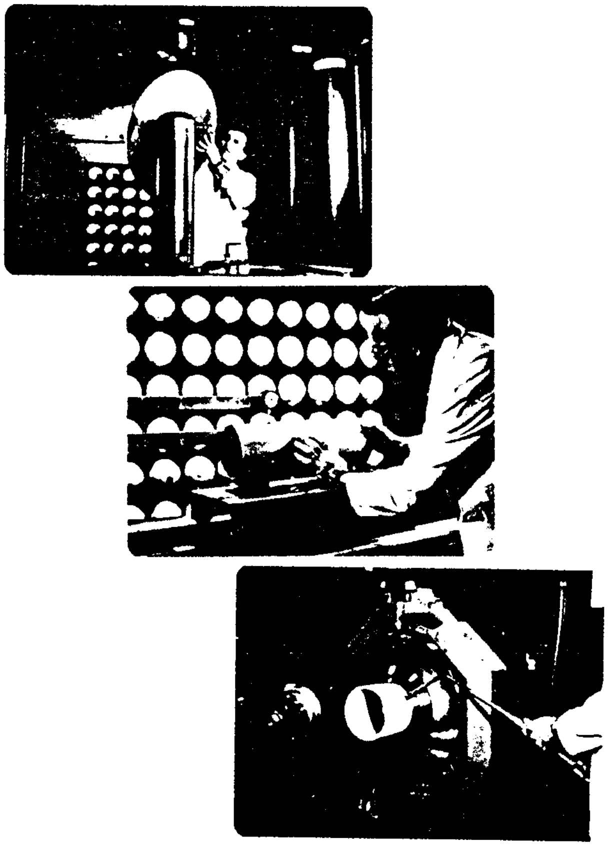
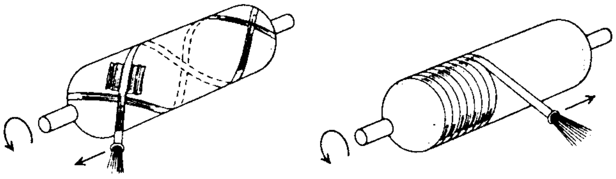


Fig. 1 - Deep draw and spin liner fabrication

OVERWRAP - The liner is completely filament wound with fiberglass or Kevlar in epoxy resin using interspersed helical and hoop patterns as illustrated in Figs. 2 and 3.



Helical Winding

Circumferential (Hoop) Winding

Fig. 2 - Winding patterns

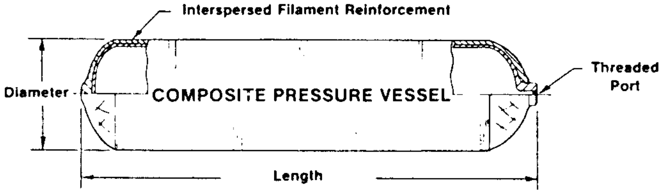

Interspersed Filament Reinforcement
Threaded Port
Diameter
COMPOSITE PRESSURE VESSEL
Length

Fig. 3 - Composite pressure vessel

A typical two spindle helical winding machine is shown in Fig. 4.

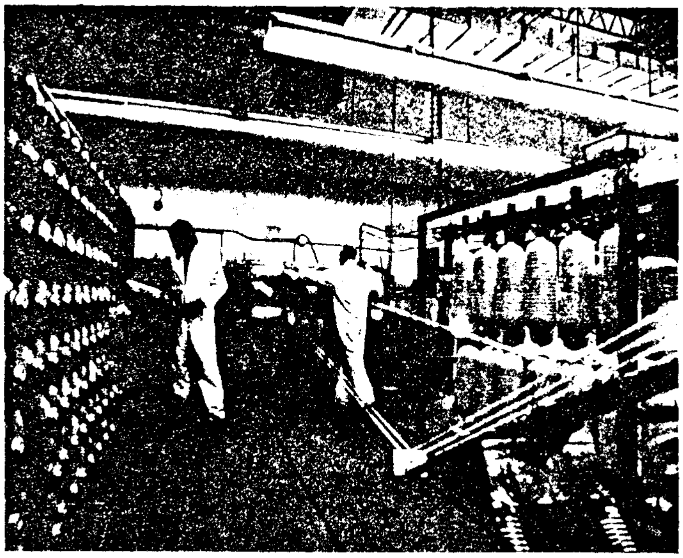


Fig. 4 - Typical two spindle helical filament winding machine

After overwrapping, a polyurethane coating of the desired color is applied to the cylinder (Fig. 5) and it is cured (Fig. 6) in an oven at 300°F. Completed cylinders are shown in Fig. 7.

LABEL - The label on a composite cylinder is often overwrapped in place with clear fiberglass hoop wrap. The cylinder serial number is stamped on the side or end of the boss to provide additional positive identification. Retest dates can be stamped on the exposed neck of the cylinder.

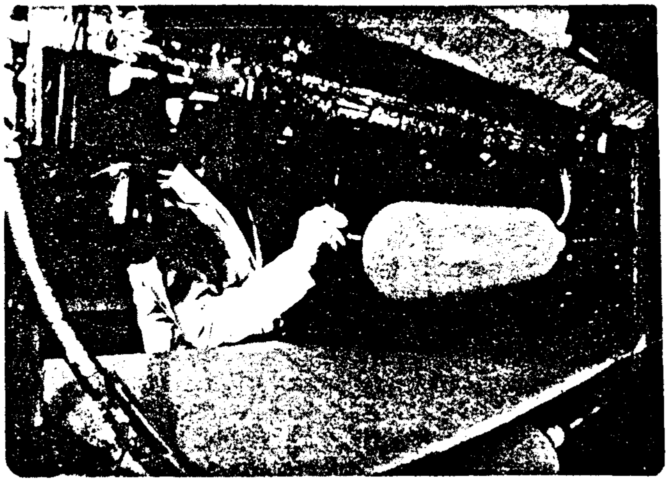


Fig. 5 - Painting cylinder

Fig. 6 - Oven curing cylinder

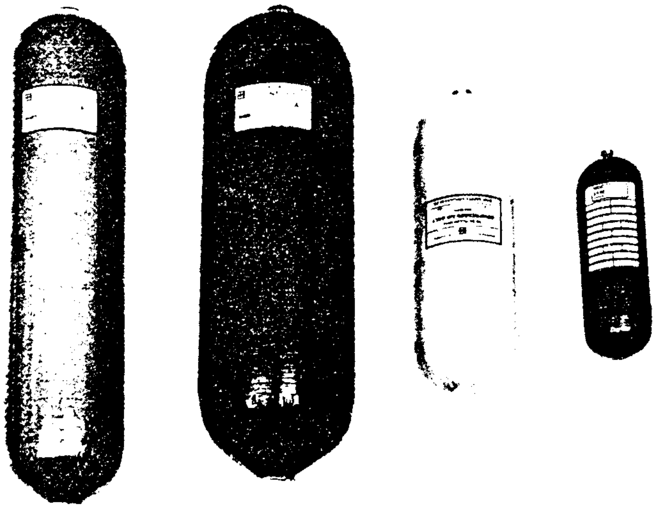


Fig. 7 - Typical fully wrapped cylinders

TESTING - Some of the tests required by the DOT to assure that the composite cylinder is as safe as the all metal cylinder for transportation are as follows: acceptance hydrotest including test pressure application (5/3's operating pressure) and measurement of temporary and permanent expansion (Fig. 8); and product qualification tests including pressure and temperature cycle (Fig. 9), burst (Fig. 10), gunfire (Fig. 11), bonfire (Fig. 12), flaw growth resistance (Fig. 13), and impact (Fig. 14).

An independent inspection system ensures that production units are made in the same manner as the test units. There is also non-destructive inspection of all units (Fig. 15) plus destructive testing on 1 or 2

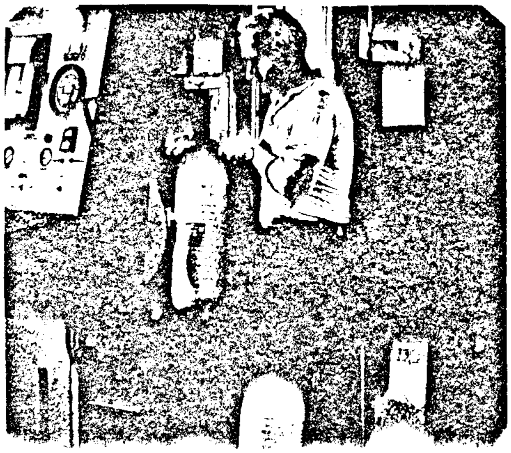


Fig. 8 - Vessel hydrotest

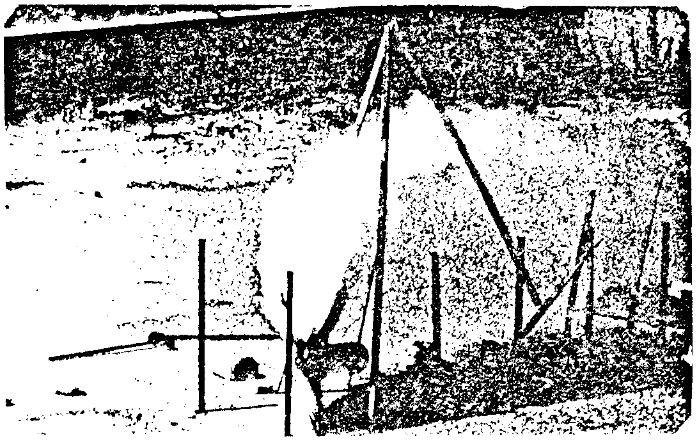


Fig. 11 - Gunfire test showing no fragmentation of tank

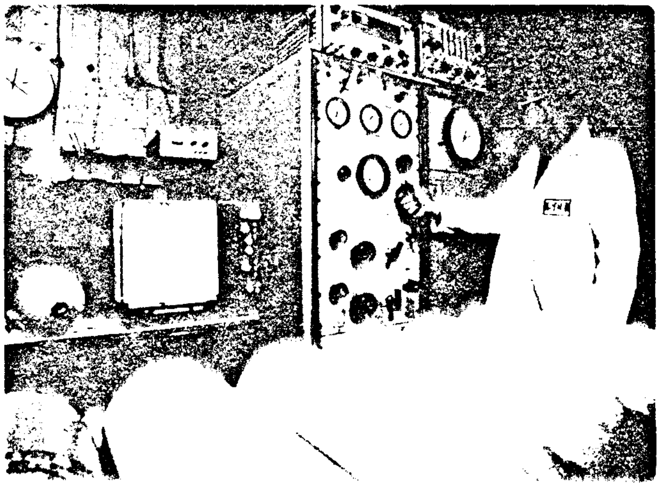


Fig. 9 - Pressure cycling of vessel

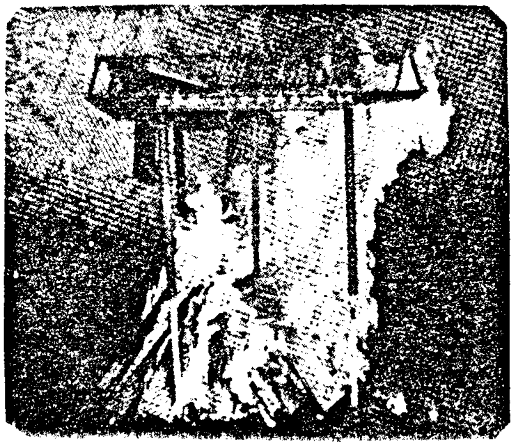


Fig. 12 - Bonfire test showing no explosion

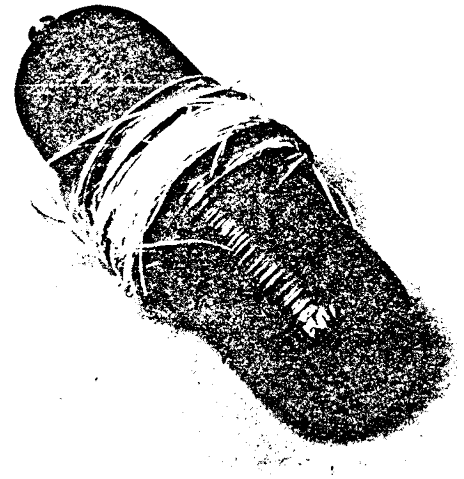


Fig. 10 - Burst test showing no fragmentation of tank

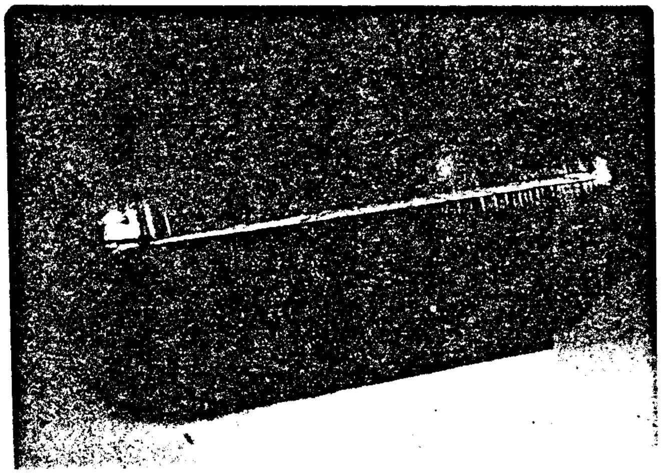


Fig. 13 - Exaggerated flaw growth test showing no increase in flaw size during pressure cycling

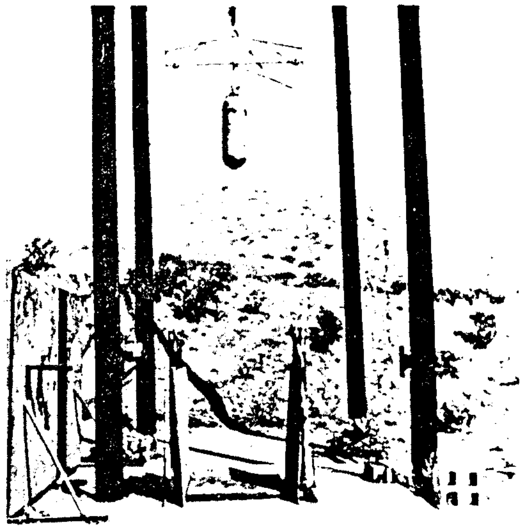


Fig. 14 - Impact test showing no performance degradation

Fig. 16 - Drag abuse test showing no performance degradation

Fig. 15 - Internal examination of cylinder with boroscope

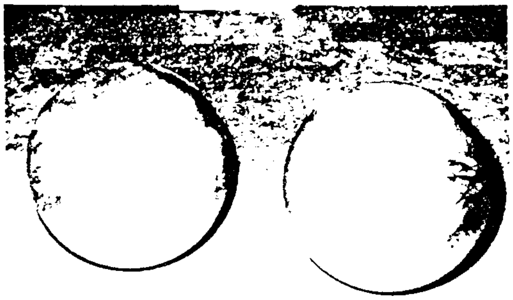


Fig. 17 - Metal liner assembly ready for winding

samples from each lot of 200 production units.

Some unusual tests have been conducted to assure that units meet specific customer requirements. For example, a drag abuse test (Fig. 16) was performed by attaching a cylinder to a car, dragging it at moderate speeds, hitting and bouncing it on curb, and then showing no degradation of performance by burst testing.

SPHERES - As pictured in Figs. 17-22, spheres are manufactured in much the same way as cylinders. However, they are not now being produced in large quantities and are not DOT-authorized.

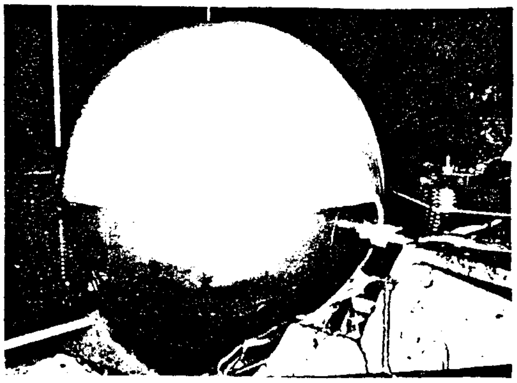


Fig. 18 - Initial filament windings applied to liner

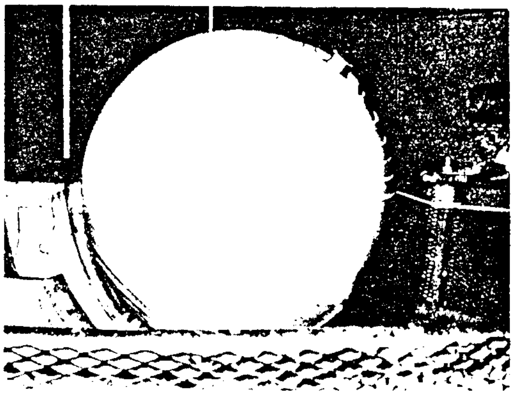


Fig. 19 - Partially completed filament overwrapped liner

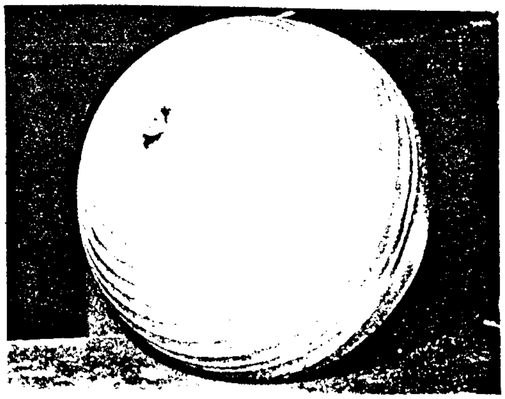


Fig. 20 - Pressure vessel after winding and curing

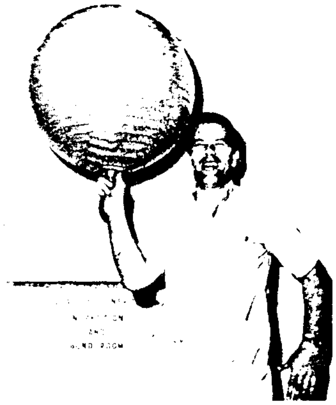


Fig. 21 - Light weight composite pressure vessel after proof test

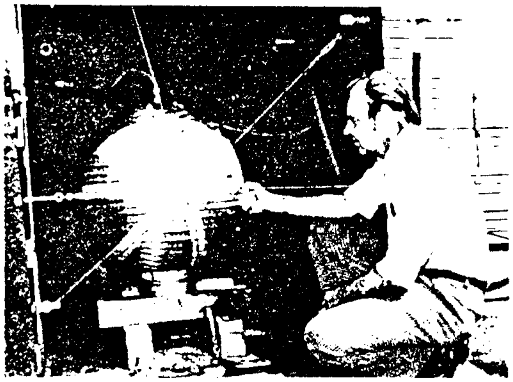


Fig. 22 - Performance test set-up

ADVANTAGES

The major advantage of composite pressure vessels is light weight; they weigh up to 50% less than comparable metal tanks. In addition, they are usually lower cost than high-performance all-metal aerospace tanks. Another important advantage is enhanced safety because of the leak-before-burst failure mode designed into composite tanks using fracture mechanics technology.

Other features of filament wound tanks include:

- o Long life, low maintenance, rust free
- o Proven in cyclic fatigue and static loading
- o Compatible with cryogens, propellants, gases, liquids
- o Non-shatterable under ballistic impact
- o Demonstrated resistance to high humidity/temperature combinations, fungus, salt spray, sand, dust, sea water, sunlight
- o Meet normal vibration, shock, acceleration and acoustic requirements
- o Interchangeable with heat-treated steel, aluminum, nickel-base alloy and titanium vessels

USES

Composite tanks are ideal where light weight and high strength are important. Applications include containment of fluids for the following systems:

- Spacecraft
  - Propellant tank pressurization
  - Engine or instrument fuel
  - Engine purging
  - Auxilliary power
  - Astronaut life support
  - Cold gas thruster
- Missile
  - Guidance power source
  - Cryogenic instrument cooling
- Aircraft and Helicopter
  - Inflation of escape slide and life raft
  - Emergency actuation of door, landing gear and other devices
  - High altitude gaseous O_2
  - Pneumatic engine starting
  - Emergency actuation of escape seats
  - Hydraulic accumulator
  - Cryogenic instrument cooling
  - Engine compartment fire extinguisher
  - Inflation of float for landing in water
  - Pnuematic gun drive power
  - Crew walk around bottle for in-flight breathing, and individual passenger use
- Hydrofoil Ship
  - Fire extinguisher
  - Clearing of clogged water inlet
  - Emergency actuation power
- Ground Service
  - Emergency breathing for fire fighter, miner and rescue worker
  - Automotive fuel such as compressed natural gas or hydrogen
  - Over-the-highway trailer tubes for industrial compressed gas
  - Medical or industrial compressed gas

Figs. 23-29 show typical applications.

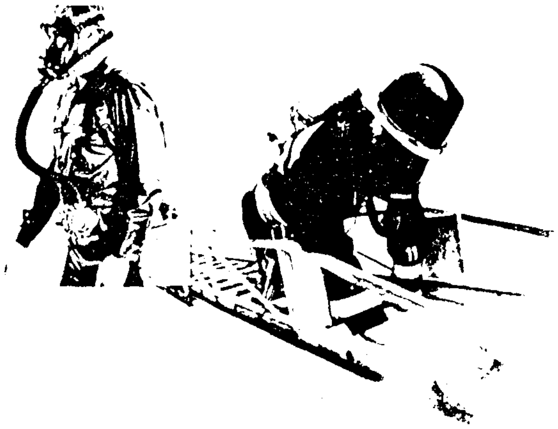


Fig. 23 - Cylinder for fireman's breathing apparatus

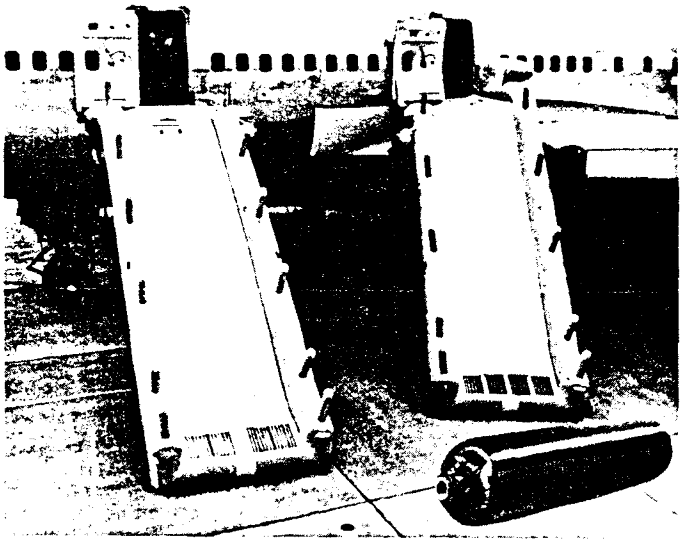


Fig. 24 - Cylinder for commercial aircraft escape slide inflation system

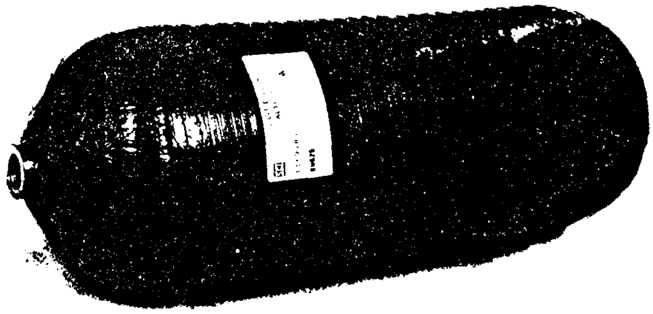


Fig. 25 - Cylinder for helicopter flotation bag inflation system

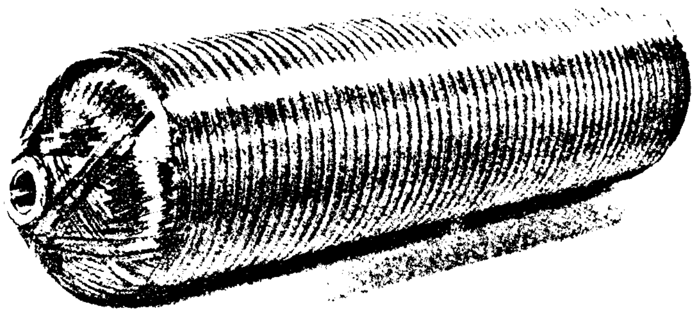


Fig. 26 - Cylinder for hydrofoil missileship fire extinguishing system

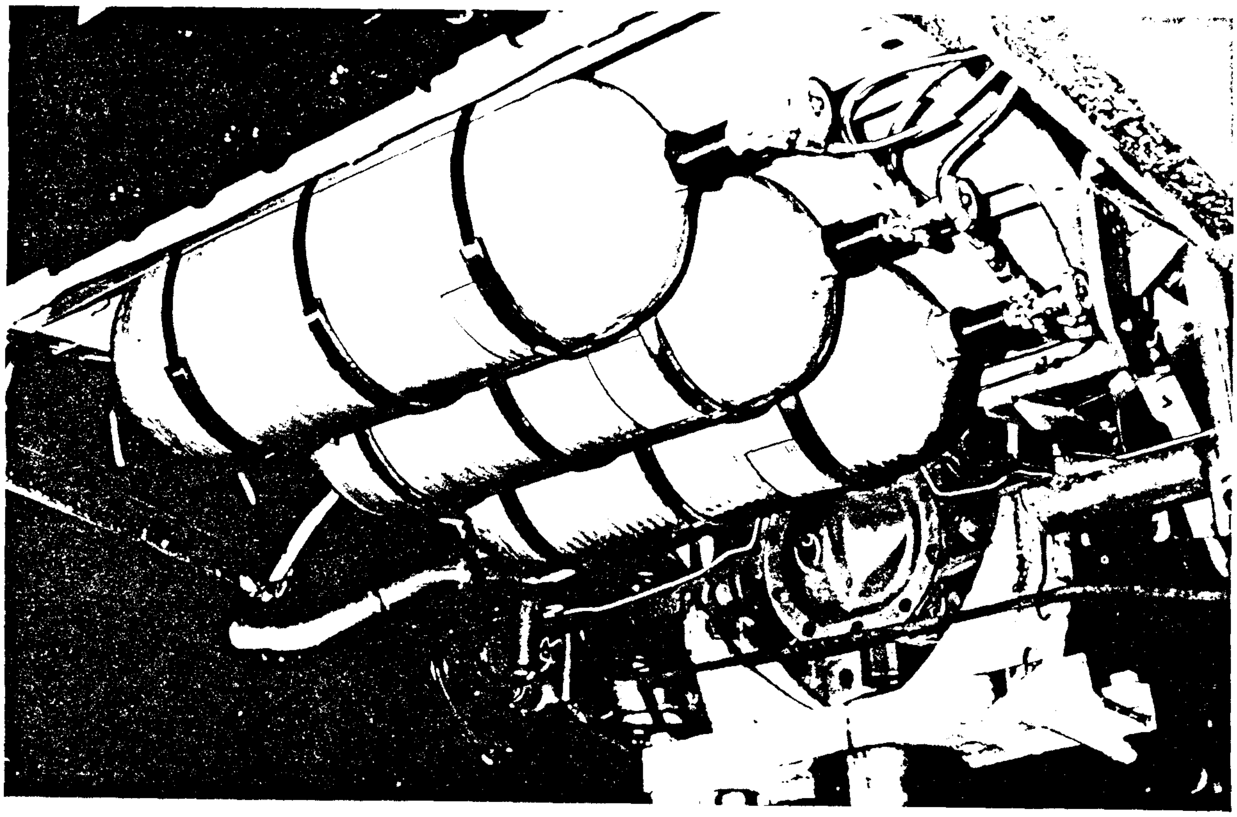


Fig. 27 - Experimental compressed natural gas fuel tanks for automobiles

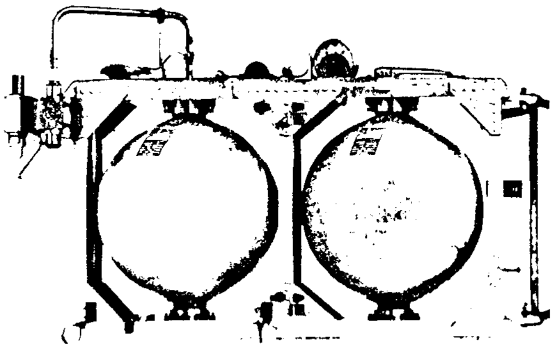


Fig. 28 - Spherical gas storage tanks for aircraft auxilliary power system

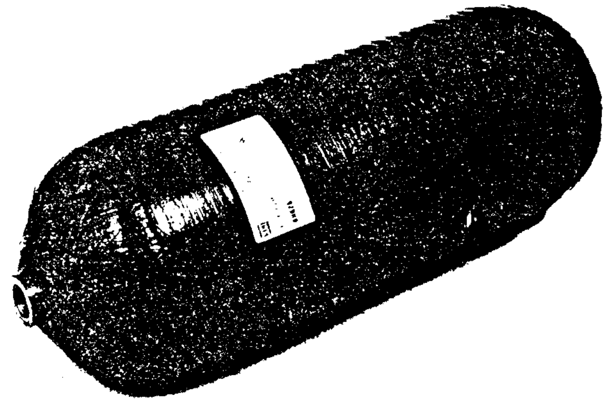
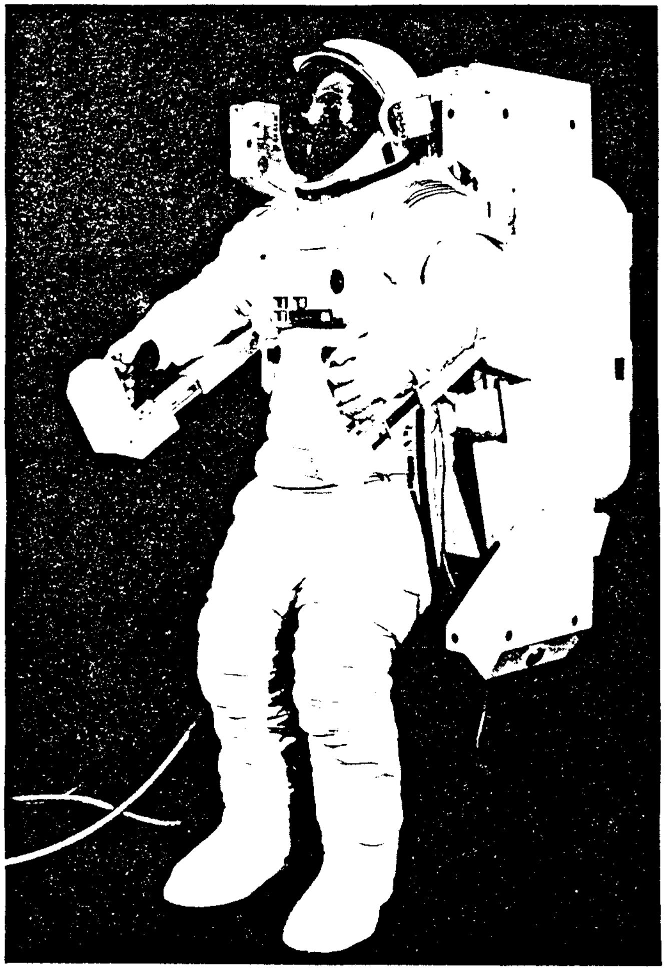


Fig. 29 - Cylinder for manned maneuvering unit thruster system

SUMMARY AND CONCLUSIONS

Advanced filament wound pressure vessels are the result of applying aerospace materials and processes to manufacture useful commercial products. The transfer-of-technology has been successful by carefully retaining the essential parameters of the technology while modifying those that cause high costs characteristic of the aerospace industry. Thus, advanced technology but lower cost commercial composite pressure vessels are now available for military/aerospace applications.



For whitewater, wilderness tripping, as well as casual recreation, Mad River Canoe's Courier is a 14-foot, 10-inch craft (32 inches at the gunwale line) that weighs only 45 pounds because it is fabricated of Kevlar material. The Courier has been the winner of the combined slalom/downriver solo class at the Whitewater Nationals for the past 2 years.

COMPRESSED AIR MAGAZINE • SEPTEMBER 1984

COMPOSITES – THE NEW WAVE

Advances in plastics technology have led to development and increasing use of a new class of plastics-based materials—the composites. These combine a resin and one or more types of high-strength fibers or other additives. Usually, thermosetting resins, such as epoxy or polyester, are used because, once set, they will not soften with heat, a fact that is important in high-temperature composites fabrication. The mixture normally consists of 50 percent or more of the reinforcing additive, differentiating composites from the broader classification known as reinforced plastics.

The most widely used reinforcement is glass fibers. Generally, these shorter fibers are used in relatively inexpensive applications that use such high-speed fabrication techniques as injection molding.

Continuous fibers, such as boron, graphite, and Kevlar, Du Pont's aramid fiber, usually are reserved for high-performance applications, where expense is not the primary consideration. Carbon/graphite fibers may cost between $20 and $25 per pound, while commercial grades of boron fibers may command $200 to $250 a pound. In composites, the fiber is used to distribute the load evenly throughout the resin matrix, making the composite as much as 20 to 30 times stronger than the hardened resin by itself.

Because all composites are anisotropic, the maximum strength and rigidity is in the direction of the fibers, regardless of the type of fiber used. Composites, therefore, can be tailored by such means as lamination or lathe-type filament winding, to achieve optimum strength and stiffness for a particular application. In essence, the orientation of the fibers is carefully altered with each succeeding layer until the desired results are obtained.

Using high-performance fibers—that is, boron, graphite, or Kevlar fiber—bound in a matrix of epoxy, vinyl ester, polyurethane, or polyester resin, composites can actually be made stronger than steel, lighter than aluminum, and more rigid than titanium. That, undoubtedly, is why aerospace has been in the forefront of composites development and application.

Airframe construction makes use of graphite/epoxy composite to provide about the same strength and rigidity as aluminum. But, it is up to 44 percent lighter—a crucial factor in designing for performance and fuel efficiency. An example of such design is the Lear 2100 business aircraft, a turbine-powered, fan-driven plane with an airframe constructed entirely of carbon/graphite epoxy composite. This plane's overall weight is about 35 percent less than competing turboprop aircraft, and its performance is exceptional: a ceiling to 10,000 feet higher; a top speed 50 to 100 mph faster; and fuel consumption about half, that of similar turboprops.

Two of the newer commercial jetliners, the Boeing 767 and 757, use both Kevlar fiber and carbon/graphite composites in several secondary structures, thereby eliminating 1250 and 1500 pounds of structural weight, respectively. Composites have also been used on McDonnell Douglas DC-10s for the better part of a decade, and on Lockheed L-1011s, as well as other U.S. and foreign-made aircraft.

Approximately 1400 pounds of graphite epoxy composites are used on the wing skins, spars, fuselage panels, and control surfaces of the AV-8B Harrier II, built for the U.S. Marines by McDonnell

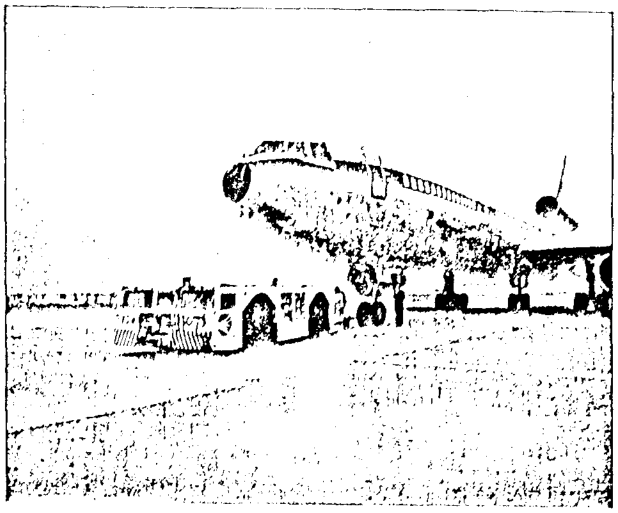
Douglas. This accounts for nearly 28 percent of the V/STOL (vertical/short takeoff and landing) fighter aircraft's structural weight, and represents a 20 percent weight savings overall.

The Navy's F-18 fighter, also built by McDonnell Douglas, uses 1300 pounds of graphite epoxy on its horizontal and vertical tail boxes, wing and tail control surfaces, speed brakes, and doors, saving about 25 percent in weight.

A major development program focusing on use of composites is also underway for helicopter airframes. Sponsored by the U.S. Army, the Advanced Composite Airframe Program (ACAP) has a goal to produce the technology needed for the design and manufacture of new helicopters with all-composite airframes.

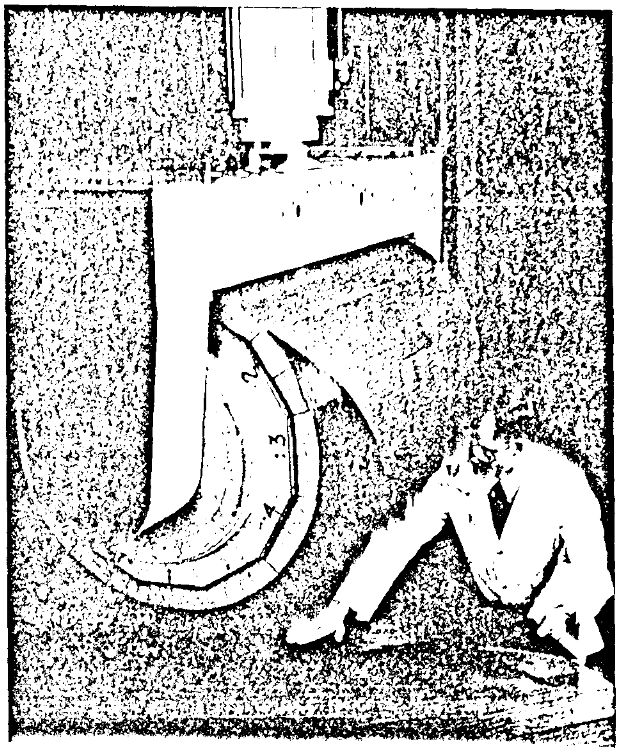
NASA, of course, is another strong believer in composites, as evidenced by the use of 4000 pounds of the material on the shuttle orbiters. The 60 × 15-foot bay doors of the Columbia are made entirely of graphite composite, and the craft is 2700 pounds lighter than if it were composed entirely of aluminum structures.

Automakers are also using composites. Drive shafts made from composites such as Celion, carbon and glass fibers in an epoxy matrix from Celanese Plastics & Specialties Company, have already proved themselves during rugged endurance racing, and graphite composite shafts are planned for introduction on trucks by both Ford and General Motors.



The DC10, shown here being maneuvered with ease by Tow Tractor equipment made by Ingersoll-Rand's Mining Machinery Group, has been fabricated with composites for the better part of a decade.

Northrop Corporation has begun manufacturing the first test parts for large aircraft composite fuselage structures. It uses several automated manufacturing processes, such as a gantry robot with a Northrop-developed roller head (shown here), to build the large graphite composite parts.



FIBER SOURCES

America's largest producer of graphite fibers is Hercules, Inc., Wilmington, Del., and the company's 1984 production will be an estimated 2,500,000 pounds. In addition, it is the country's only producer of polyacrylonitrile (PAN) the material from which carbon fibers are made.

Two years ago, Hercules announced formation of a joint-venture company with Pechiney Ugine Kuhlmann Corporation, Paris, France. Known as Societe Europeenne de Fibres et Composites, the new company was set up to manufacture graphite fibers in France for the European market.

Other major U.S. manufacturers of carbon fibers include Celanese Corporation, Union Carbide, the Hitco Division of Armco, Inc., Great Lakes Carbon Corporation, and the Carbon Division of Stackpole Corporation.

A large percentage of the world's boron fiber production is consolidated in two U.S. companies—The Specialty Materials Division of Avco and Composite Technology, Inc. Boron fibers are considerably bigger, coarser, and more rigid than graphite fibers, and are very expensive to produce. Their use has been primarily in aerospace applications, and, occasionally, in high-ticket consumer items.

Kevlar fiber is manufactured by Du Pont. While it is high in tensile strength, it is comparatively low in compression strength and it has the lowest density of the major composite fibers. Costing about $10 a pound less then graphite fibers, Kevlar is likely to find additional use in a wide range of consumer applications.

The industry sees composites offering design flexibility not available from other materials. In many instances, fabrication can be simplified by consolidating parts, and high strength-to-weight ratios provided by composites can help designers reach better fuel efficiencies. In the 1984 Corvette from Chevrolet Division of GM, a new fiber glass spring is fabricated in one piece, instead of the ten parts that would be needed if it were made of steel. Also, the spring weighs only 8 pounds, compared to the 41 pounds of a similar metal spring.

Consumer products also are turning to composites for applications requiring high-performance characteristics. Fiber glass fishing poles have been on the market for decades, but the new generation makes use of graphite composites. These have also been selected for use in tennis racquets, golf clubs, and hand tools, and will probably be seen in poles used by skiers and pole vaulters, as well as in the hulls of sailing craft. Du Pont's Kelvar fiber has been used successfully for several years in the manufacture of canoes, as well as on bulletproof vests for law-enforcement personnel.

Composites -how they'll make cars lighter, stronger

New techniques "knit" materials together to form composites: superstrong, lightweight substitutes for present components

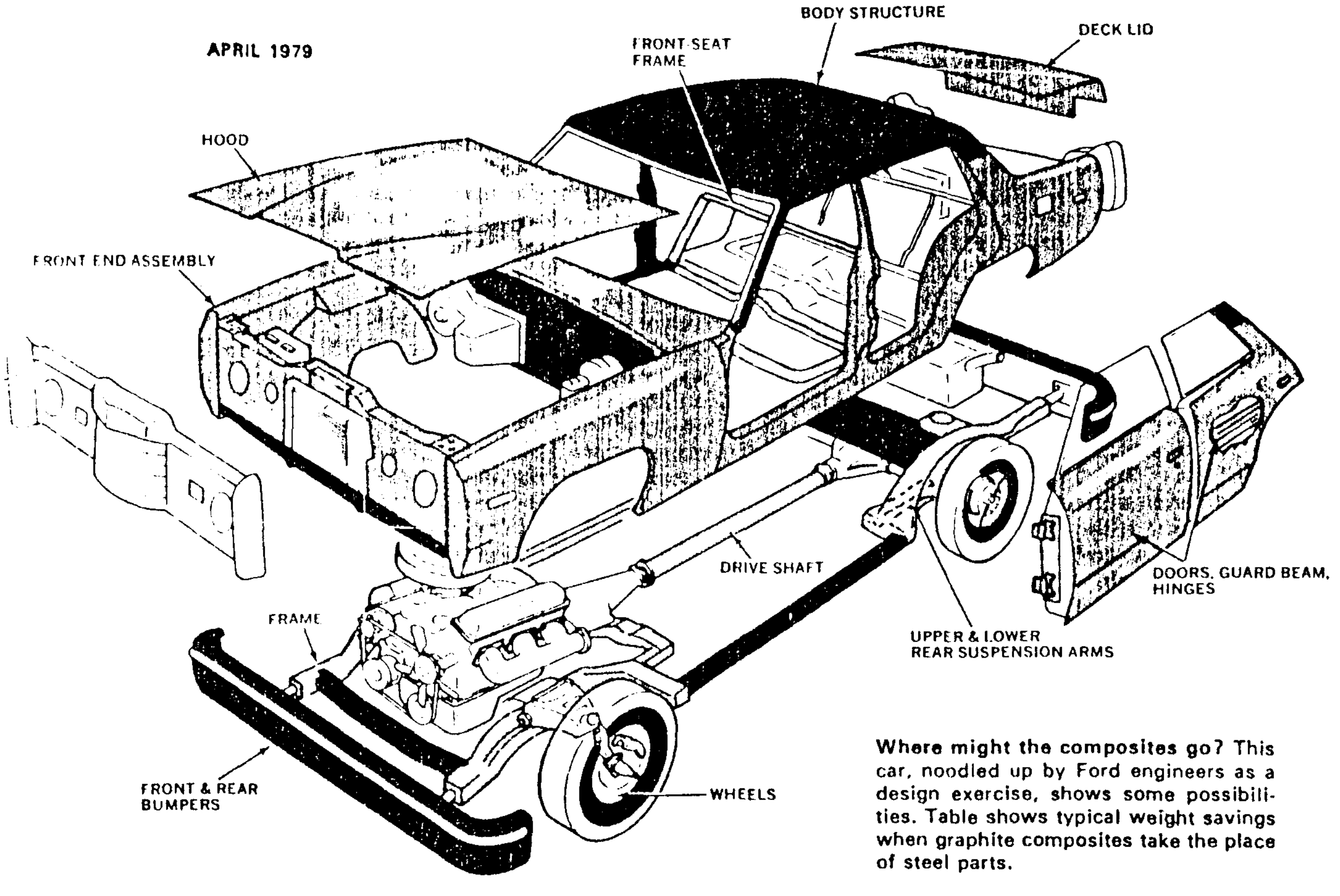
By E.F. LINDSLEY

Knitted auto parts? Maybe so. Car makers are under intense pressure these days to cut large amounts of weight to increase gas mileage. And one area they're exploring is the use of high-strength, lightweight composite materials to replace some of the steel now used

Continued

Popular Science

APRIL 1979



Where might the composites go? This car, noodled up by Ford engineers as a design exercise, shows some possibilities. Table shows typical weight savings when graphite composites take the place of steel parts.

in passenger cars and trucks.

A composite is a substance made of two different materials, each with its own unique physical characteristics. Each material contributes certain advantages, and the resultant substance is better than either alone. Reinforced concrete is one common composite. With steel rods supplying tensile strength and the concrete supplying resistance to compression, the resultant material is a far better building material than either alone.

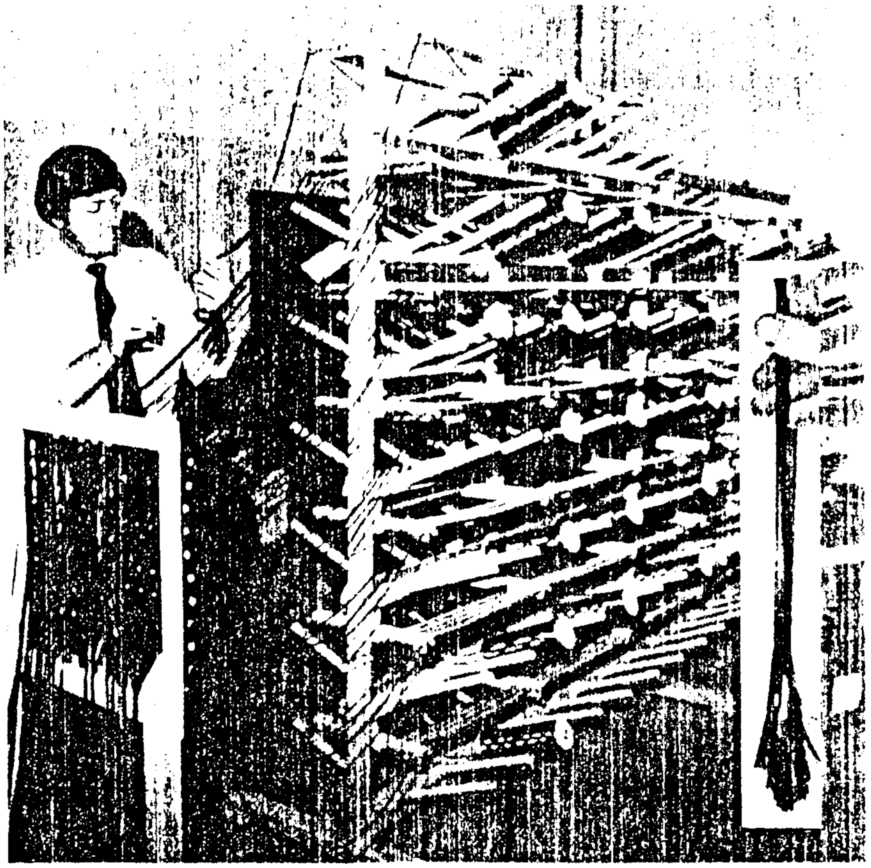
Composites similar to those now being studied for automotive use were first developed for the combination of extreme strength and lightness they could give to airplane structures. Later they contributed their special combination of strength, rigidity, and lightness to golf-club shafts, racing-bicycle frames, fishing rods, and other sports gear [PS, April '75]. Now, engineers are trying to put these same qualities to work to make future generations of cars more fuel efficient.

Composites under study for use in automobiles are generally made of fine, high-strength strands of carbon embedded in a plastic bonding material. The fibers are often called graphite, which they are not. Graphite fibers *were* used in the aerospace industry starting in the 1960's, and the name stuck. Most carbon these days comes from what the people in the business call PAN (polyacrylonitrile), an acrylic material much like that used in fabrics. To make a carbon fiber suitable for a composite, PAN is heated under tension in air to oxidize and stabilize its structure, then heated again in the absence of air, still under tension, at 1200 to 1600 degrees C (2192 to 2912 degrees F) to drive off the noncarbon portion.

The tension is vital, according to Ken McHugh of Monsanto: "If you don't keep this fiber under tension all the time you're processing it, if you don't keep those molecules straightened out, you get an amorphous thing with no strength."

Another source of carbon fiber is common pitch, processed in a somewhat different method developed by Union Carbide.

Strength and load patterns



In Graftek's pultrusion process, carbon fibers are pulled into a single strand, coated with resin, and passed through a heat die to emerge as a stiff rod.

The bonding agent used to hold the resultant minute (about seven-micron-dia.) fibers together is determined by the shape of the final product and how it is to be formed. For example, at the Graftek Division of Exxon Enterprises in Raleigh, N.C., I saw extremely stiff composite rods made by what engineers call a pultrusion process. Fibers were pulled off a rack of spindles in a rope-like tow, coated with a polyester resin, and drawn through a heated die to emerge as a stiff rod. Polyester is used, says Graftek research director Vance Chase, "because it cures very rapidly." Epoxy is used in other kinds of construction; it cures more slowly and is fine for lay-up forming. In other cases where a press-forming process is best, thermoplastic resins are attractive.

Theoretically, composites of various kinds could save an enormous amount of weight. "If you take a steel bar and a graphite-bonded bar, the composite has about one-fifth the weight and about the same strength in tensile," says Vance Chase. If that were the whole story, the weight-cutting potential would, indeed, be fantastic. Unfortunately, nothing in engineering is quite that simple, as Chase was quick to point out. Main problem: Carbon materials are "anisotropic." That means that, unlike steel, they're not equally strong in all directions. Designers must always keep in mind the direction of the load and how the fibers must be oriented to handle it. In a push rod, for example, the loads are pretty much in one direction and the fibers can be linear. Parts with more complex load patterns require very careful load analysis and a carefully planned fiber-placement strategy.

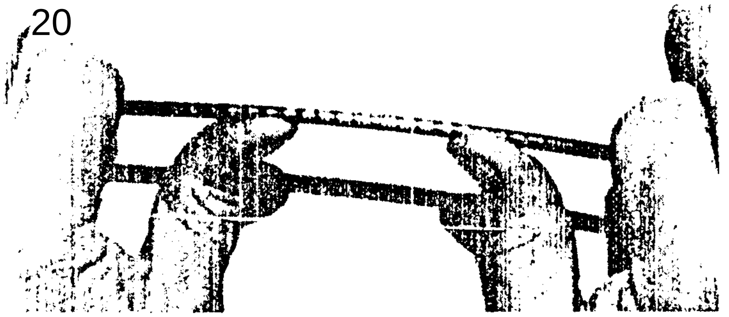
An example would be a connecting rod. I was told at Graftek that, after a period of experimentation and study, they'd worked out the problems of the top end of the rod and were now doing a very detailed analysis of the lower end.

Composite candidates

With such inherent restraints, can composites do the job? How much weight might they save? According to auto mechanic Smokey Yunick's sources, the auto companies feel they've got to replace 400 to 500 pounds of existing car with composites to meet mileage goals set by the government.

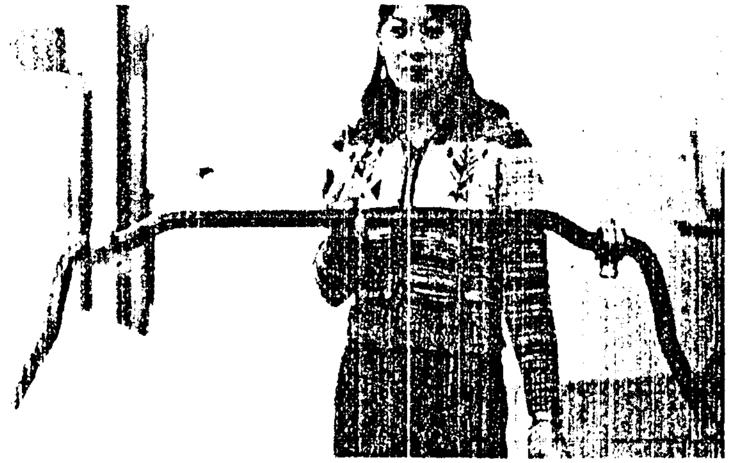
Where might this substantial savings come from? I was surprised to find that it wasn't necessarily from glove-box doors and floor pans, as I'd imagined, but also from connecting rods, pistons, push rods, coil and leaf springs, sway bars, drive shafts, and even—maybe—crankshafts.

Work is progressing in other directions as well. Ford, for example, recently announced that a



Though just 3/16-inch thick, this composite test rod resists bending by the effort of even the strongest person.

Flat form of carbon fibers is used for layup and wrap forming. Fiber orientation determines direction of strength.



Sway bar makes an ideal composite candidate, since stiffness and springiness are inherent and weight saving is significant.

How graphite composites could save weight

	STEEL	GRAPHITE	REDUCTION
HOOD	40.0 LBS.	15.0 LBS.	25.0 LBS.
DOOR, R. H. REAR	30.25	12.65	17.60
HINGE, UPPER L. H. FRONT	2.25	.47	1.78
HINGE, LOWER L. H. FRONT	2.67	.77	1.90
DOOR GUARD BEAM	3.85	2.40	1.45
SUSPENSION ARM, FRONT UPPER	3.85	1.68	2.17
SUSPENSION ARM, FRONT LOWER	2.90	1.27	1.63
TRANSMISSION SUPPORT	2.35	.55	1.80
DRIVE SHAFT	17.40	12.00	5.40
AIR CONDITIONING, LATERAL BRACE	9.50	3.25	6.25
AIR CONDITIONING, COMPRESSOR BRACKET	5.63	1.35	4.28

composite air-compressor support bracket in 1980 cars will replace steel, at a saving of five pounds. Coil and leaf springs are also candidates; composites have high fatigue resistance, which makes them ideal for this purpose. In fact, huge truck leaf springs are now being field tested.

Valve springs also look like a good bet, and so do sway bars and drive shafts. The latter have to take the torque between the transmission and the differential and be stiff enough not to whip or vibrate. I saw one experimental shaft made with an inner aluminum tube with a wall thickness of about 0.07 inches and a bonded-on outer covering of fiber composite that looked to be about 0.030 inches thick. The aluminum handles the torque and the composite provides the stiffness. There was another shaft under test made of all composite.

Not home free yet

There are still serious problems, of course, as with any new technology. For example, how do you attach the fittings at the end of a drive shaft? With a steel shaft you simply weld on your fittings. With composite and aluminum, welding is still possible. But in solid composite, an adhesive bond is necessary. The bonding tried so far seems to work. But will it come unglued under aging, temperature extremes, and other conditions?

Perhaps an even more serious question involves temperature sensitivity. Temperatures, high or low, are no problems for the carbon fibers, but the bonding resins are typically not good for over 250 to 300 degrees F. Graftek says polyamide binders will operate at 600 degrees. That's fine, but to hold that temperature limit in the center of a piston crown you've got to conduct heat to the ring bell quite rapidly, and composites are not good heat conductors.

And what about heat conduction from the lower-end bearings of composite connecting rods? Normally a metal rod is cooled by oil flow through it, plus heat conduction to the outside surface where oil spray and moving air flush heat away. If you don't get that heat conduction through the rod, what cools the bearing? Do you increase oil flow? As far as I could learn, nobody has the answer to these questions yet. But no doubt they will be the object of a lot of research-and-development effort.

As for production, low-cost, highly efficient processes are needed. One Monsanto spokesman said, "We sent engineers to the West Coast to look at aerospace techniques, but they were 99 percent useless—geared for 400 parts a year, and we want 400 parts an hour."

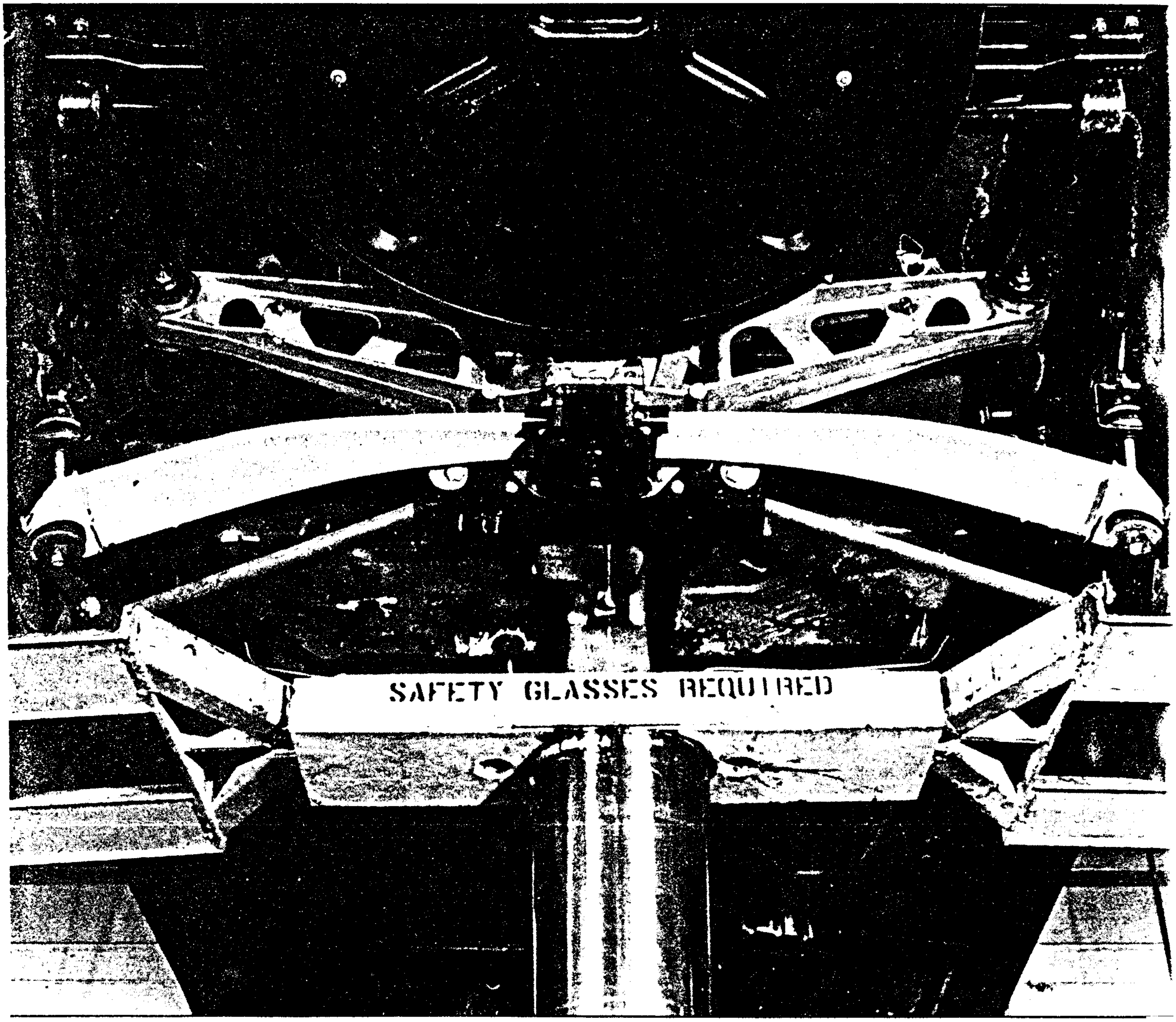
And finally, there's that ultimate question: How much will it cost to get the benefits we want? In an airplane structure, a pound saved is worth a lot. Even over-the-road truckers, intrigued by the lighter composite leaf springs, talk of being willing to pay $5 to save a pound of weight. But to make composites really attractive in passenger cars, the cost of these materials must drop drastically.

Right now, they're going for as much as $37 a pound. This will drop some when volume picks up. Some experts think PAN-based materials will get into the $5- to $7-a-pound range quite soon, and there is apparently hope that pitch-based materials may ultimately reach $2 a pound.

All together, there are still more questions than answers. Smokey was talking about connecting rods when he said it, but what he said sums up my impression of the future use of composites in cars: "I think the thing that makes it interesting is that *they are going to do it,* but the technologies are still going to have to come."

PLASTIC FANTASTIC!

New Corvette fiberglass rear spring ushers in a new era of lightweight suspension components for performance cars



New fiberglass lightweight rear spring is standard equipment on all '81 Corvettes fitted with basic suspension. Optional HD suspension makes use of conventional steel spring.

A filament-wound, rear suspension transverse single leaf spring for the '81 Corvette was chosen for the Grand Design Award at the 36th Annual Conference and Exhibit of the SPI Reinforced Plastics/Composites Institute held at the Sheraton Washington Hotel in Washington, DC. The eight-pound spring also won the Blue Ribbons in the Transportation and Market Development categories and earned for General Motors the Steuben glass sculpture "Counterpoise" traditionally given by Owens-Corning Fiberglass Corp.

The "Lite-Flex" leaf spring represents the joint development efforts of Chevrolet Engineering Center, Inland Division, and General Motors Manufacturing Development, with Merlin Technology providing multi-layered finite element analysis for the project. Filament wound with 70 percent continuous-strand glass fiber in an epoxy matrix, the eight pound spring achieves an 80 percent saving in weight compared to the 41 pound multi-leaf steel spring it replaced. The practicality and durability of materials, design, and processing have been proven in a year of development that included 175,000 test miles in hot desert and frozen tundra climates. Success of the spring is expected to spur wide use of similar composites. ☐

7.6 Filament-Wound Pressure Vessels

Filament-wound vessels are fabricated by continuously winding a filament over a mandrel of the shape and size of the desired vessel.[61] The mandrel can be a removable one, or one that remains a permanent part of the vessel. The matrix material is usually applied simultaneously with the winding operation. The winding of vessels can be accomplished by using two independent wrapping systems oriented in the direction of two principal stresses,[62,63] or a single helical winding with the filaments laid down upon the mandrel at an angle to the axis depending upon design consideration, such as access openings, Fig. 7.27. Filament-wound pressure vessel designs must be such that the filaments are placed only where they are needed and in such a manner that they are all uniformly stressed.[64,65] For instance, in a cylindrical pressure vessel where the hoop load is twice the longitudinal load, it is necessary to have twice as much circumferential winding thickness as longitudinal thickness in order for the stresses in the filaments to be uniform. Fig. 7.28 shows the basic geometry of a typical cylindrical pressure vessel with closure heads incorporating openings. The winding angle α is that which will cover the heads and provide longitudinal strength. The angle β is the winding one that will provide the necessary hoop strength in the cylindrical portion of the vessel.

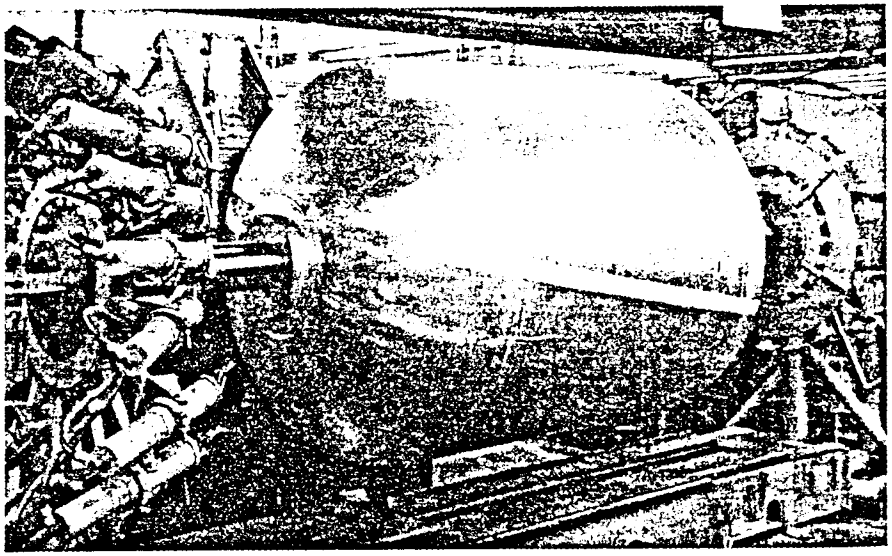


Fig. 7.27. Filament Winding of a Cylindrical Vessel[61]

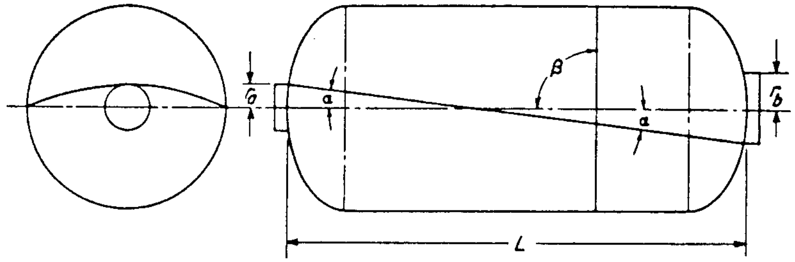


Fig. 7.28. Geometry of Filament-wound Cylindrical Vessel

The angle α can be determined from the geometry of the vessel as

$$\alpha = \tan^{-1}\left(\frac{r_a + r_b}{L}\right) \tag{7.6.1}$$

Once the angle α is known, the thickness of the windings, h_α, at this angle can be calculated by equating the longitudinal vessel load to that sustained by the filaments at this angle of inclination, Fig. 7.29*a*.

$$\frac{F_1}{\cos\alpha} = \sigma_f\, h_\alpha \cos\alpha \tag{7.6.2}$$

$$\frac{F_1}{\sigma_f} = h_\alpha \cos^2\alpha \tag{7.6.3}$$

where

F_1 = Longitudinal pressure load, lb per in. of circumference.
F_2 = Hoop pressure load, lb per in. of longitudinal length.
h_α = Total thickness of filaments in α direction.
h_β = Total thickness of filaments in β direction.
σ_f = Allowable unidirectional stress for filament material.

The thickness of the winding in the hoop direction, h_β, of the cylindrical portion can be determined by equating the hoop load, F_2, to the sum of the hoop direction component of the α and β filament windings, Fig. 7.29*b*,

$$\frac{F_2}{\sigma_f} = h_\beta \sin^2\beta + h_\alpha \sin^2\alpha \tag{7.6.4}$$

A single filament winding system with a single angle α can also be used for cylindrical vessels. In this case it must withstand all of the hoop and longitudinal loads; i.e., it must satisfy these equations:

$$\frac{F_1}{\sigma_f} = h_\alpha \cos^2 \alpha \tag{7.6.5}$$

$$\frac{F_2}{\sigma_f} = h_\alpha \sin^2 \alpha \tag{7.6.6}$$

Dividing Eq. 7.6.6 by Eq. 7.6.5, and noting that in a cylindrical vessel subject to internal pressure $F_2 = 2F_1$, gives

$$\tan^2 \alpha = 2 \tag{7.6.7}$$

$$\alpha = 54° \, 44' \tag{7.6.8}$$

Therefore, a single winding angle of 54° 44′ will result in a balanced cylindrical pressure vessel.

End nozzle or access openings employ fitting configurations that permit all of the stresses to be carried along the axis of the filaments and avoid shearing stresses.[66] The windings over these end fittings must follow a geodesic path (shortest distance between two points on a curved surface) in order to obtain the correct stress distribution in the filaments, Fig. 7.28.

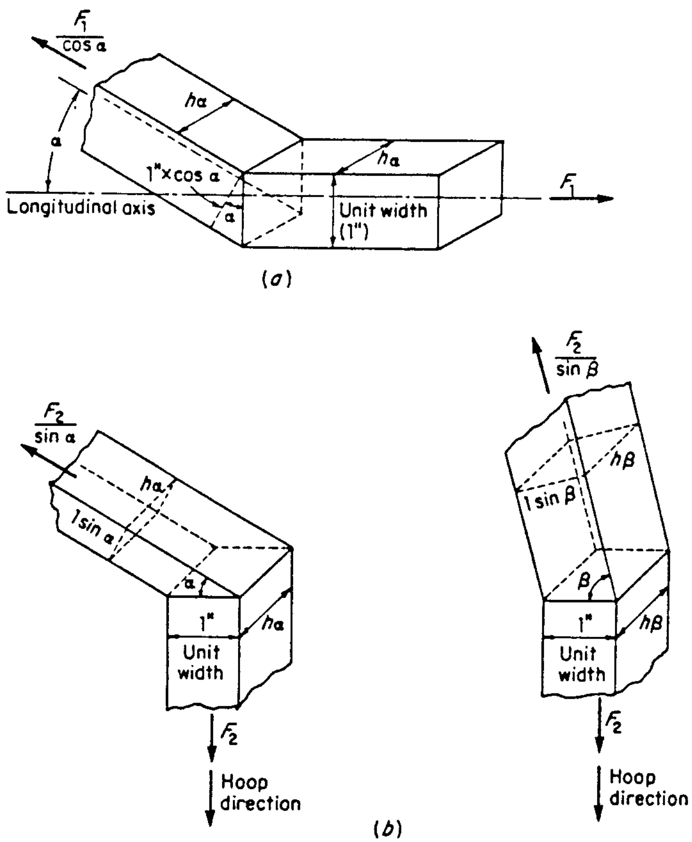


Fig. 7.29. Forces on Filaments of Filament-wound Cylindrical Vessel

Filament-wound pressure vessels are used in place of homogeneous metal ones for special applications or environments.[67,68] Some of these are:

Weight Saving. This is primarily due to the extremely high stress levels and low density[69] that can be obtained with this type of construction. It is the paramount reason for its wide usage in rocket and space flight devices.

Corrosion Resistance. This is due principally to the generally high corrosion resistance[70] of the plastic material used in the matrix. In many cases, the resins used in these materials are frequently applied to metallic structures to improve their corrosion resistance.

Low Thermal Conductivity. This is due to the general lower value of this property for plastics as compared to homogeneous metallic vessels. This has been found advantageous in cases involving solid-propellant rockets, and certain piping applications.

Low Notch-Sensitivity. Such things as scratches, poor welds, mismatched welds and other types of flaws in homogeneous metal vessels can result in notch sensitivity failures. This is avoided with filament-wound vessels due to the type construction, wherein failure of one filament does not spread to adjacent ones.[105]

High Impact and Shatter Resistance. This is due principally to the non-crack propagating construction principle of such vessels. Impact resistance is good and they are completely shatterproof, as compared to homogeneous metal ones which can fragment upon bursting.[106,107]

The prime potential application and market for filament-wound pressure vessels[71] lies in the transportation and storage of petroleum and chemical fluids where weight or a corrosion resistant environment demands the use of light weight or special and unusually expensive materials. Glass filament or high-strength steel wires presently account for the bulk of these applications; however, the use of advanced composites, such as carbon "whiskers" for filaments can result in pressure vessels with stress levels of 850,000 psi with a modulus of elasticity of 85 × 10^6 psi, and a density of 0.061 lb. per cu. in. This would mean a strength-to-density ratio of many times that of the highest presently used glass filament values, Table 7.4.

Another advantage that will be increasingly exploited as vessels increase beyond transportable size, is that of the low capital investment equipment costs and adaptability of this form of construction to large field fabricated vessels. Reinforced concrete in combination with

TABLE 7.4. PHYSICAL PROPERTIES[61]

	Filament Winding		Titanium	Steel
	"Type E" Glass	High Modulus Glass		
Density (Lb/In^3)	0.075	0.081	0.163	0.285
Tensile Yield Strength (psi)	130,000 Unidirectional Strength 270,000	115,000	150,000	220,000
Tensile Strength/Density (in)	174×10^4	142×10^4	92×10^4	78×10^4
Modulus of Elasticity (psi)	5×10^6	9.0×10^6	16.5×10^6	30×10^6
Elongation, %	2.36	1.28	0.91	0.73

prestressing is an example of a composite material that is being used for the construction of large on-site nuclear pressure vessels, paragraph 7.7, as well as the more conventional storage tanks, but need not remain restricted to these materials.

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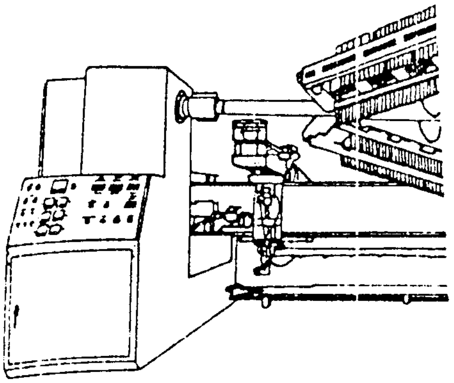

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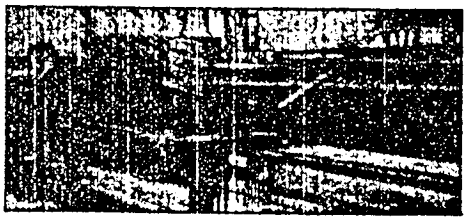
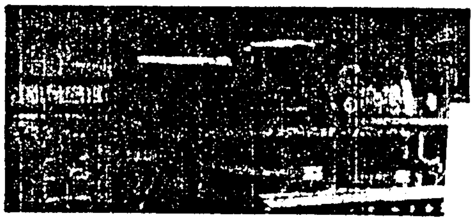


Model #10 Fiberglass Pipe Maker



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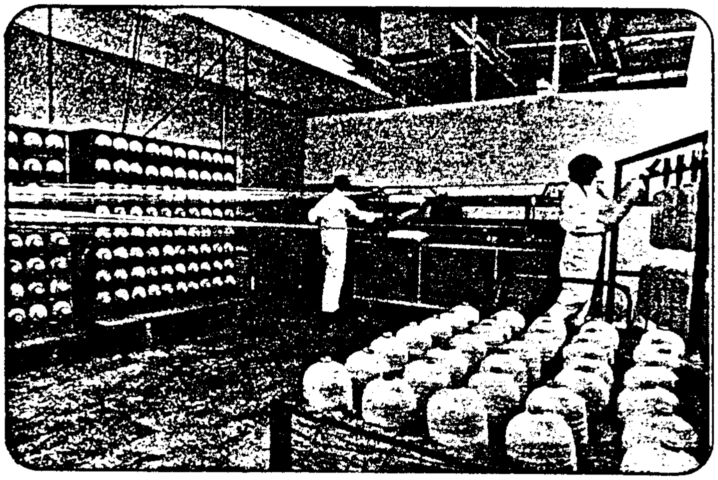
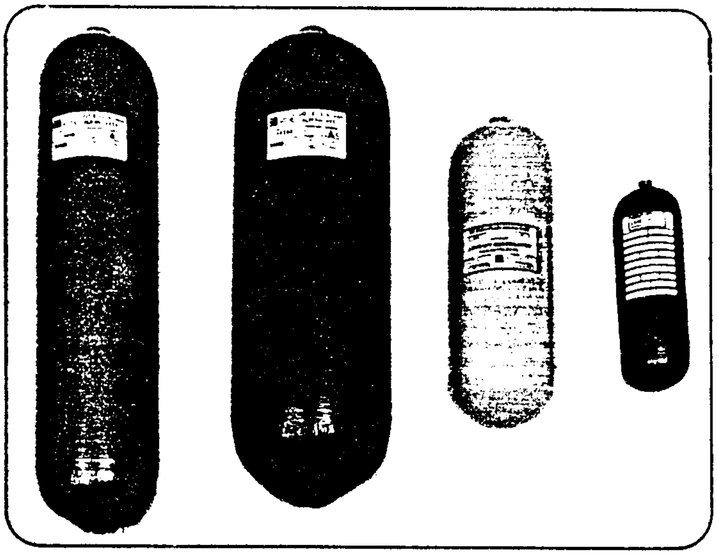


Mass Production



Filament Wound Pressure Vessels

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ALT COMPOSITE PRESSURE VESSEL MODELS

14 April 1982

Model	Volume (in.³) (min)	Service Pressure (psig)	Max Dia (in.)	Max Length (in.)	Max Weight (lb)	Boss (MS 33649)	DOT Exemption No	W.O. No.
59	511	2216	6.83	20.40	11.40	-08	7277 (G)	
59A	512	2226	6.83	20.40	11.20	-11	7277 (G)	
59B	511	2216	6.83	20.40	11.40	-08	7277 (G)	
63	1074	3000	7.90	32.80	22.00	-16	7218 (K)	
63A	1074	3000	7.90	32.70	21.00	-16	8162 (K)	
63B	1074	3000	7.90	32.70	21.50	-20	-- (K)	
129	145	3000	4.50	24.00	3.70	-05	7277 (G)	
129A	145	3000	4.50	14.00	3.00	-05	-- (K)	
129B	145	3000	4.50	14.00	3.00	-05	-- (K)	
156	1615	3000	10.22	30.55	29.50	-16	8162 (K)	11269
156A	1615	3000	9.97	30.40	28.50	-16	8162 (K)	
160	514	3000	7.10	20.50	13.00	-08	(G)	
160A	511	3000	6.95	20.72	11.25	-16	8162 (K)	61339
176	870	1543	7.35	26.56	12.00	-12	N/A	31360
180	900	3000	7.90	27.90	18.50	-16	8162 (K)	31395
181	605	3000	7.90	20.17	13.70	-16	8162 (K)	61335
182	470	3000	6.95	19.45	10.00	-16	8162 (K)	31401
183	370	3000	6.80	16.20	8.50	-16	7277 (G)	11386/11388
186	62	3000	4.70	8.25	1.80	-05	-- (K)	
186A	62	3000	4.70	8.25	1.80	-05	-- (K)	
187	650	3000	7.90	21.36	14.50	-06	8162 (K)	61335/11376
194*	1076	3000	7.90	30.10	22.00	-16/-05	7277 (G)	
200*	11000	3000	21.40	50.00	300.00	-24/-24	--	31400
205	3450	3000	12.67	41.97	56.00	-09	8162 (K)	31313/31314
208	475	3000	5.30	30.48	8.57	-16	8162 (K)	11318
209	240	3000	5.36	17.17	5.50	-16	8162 (K)	11318/11319
210	200	3000	5.36	14.93	4.90	-16	8162 (K)	11318/11319
211	65	3660	4.60	8.25	1.80	-05	N/A (K)	11290
212	140	3660	4.70	14.10	3.20	-05	N/A (K)	11290
214	44.6	3000	3.70	8.18	1.70	-05	7277 (G)	11334
215	750	3000	7.90	24.01	16.20	-16	8162 (K)	61335
216*	1000	3000	8.68	25.38	15.38	-16/-16	8718 (K)	11333
217	800	3000	7.90	25.34	17.00	-16	8162 (K)	61335/11369
218	550	3000	6.95	21.82	11.75	-16	8162 (K)	
219	360	3000	6.20	18.91	8.10	-16	8162 (K)	61342/11377
220	411	3000	6.20	21.00	8.90	-16	8162 (K)	61356
221	800	3000	6.68	32.80	15.95	-16	8162 (K)	11338
222*	7900	5000	21.00**	42.00**	360.00**	Thread 2.750-8UN-3B	N/A (K)	31323
223	260	3000	5.294	18.24	6.00	-16	8162 (K)	11343
224	306	3000	6.718	15.40	8.35	-16	8162 (K)	11344
225	45	3600	3.70	8.18	1.70	-05	N/A (G)	11347
226	125	3000	4.55	12.79	3.20	-14	8162 (K)	11324
227	514	3000	7.10	20.50	13.00	-08	N/A	11314
228	800	3000	6.79	32.80	15.95	-16	8162 (K)	11345
229*	8000	3360	25.75	N/A	72.00	0.875-14	N/A (K)	31348
270	65	3350	4.70	8.25	1.80	-05	N/A	31355
271*	2570	4000	12.71	31.58	48.00	Thread 1.625-12UN-2B	--	31357
273*	735	3200	12.47	13.11	19.00	-10	--	31365
274	260	3360	5.39	18.67	6.50	-16	8162 (K)	11373/11374
279	650	1850	6.70	25.20	7.90	-08	8162 (K)	11402/11419
280	295	1850	5.10	20.30	4.00	-08	8162 (K)	11403
281	1000	1850	7.50	30.80	12.90	-08	8162 (K)	11404/11419
282	1500	1850	9.00	31.60	18.60	-08	8162 (K)	11405

*	Double Ported Model
**	Preliminary
--	Not Qualified
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Paul Varney
Project Engineer

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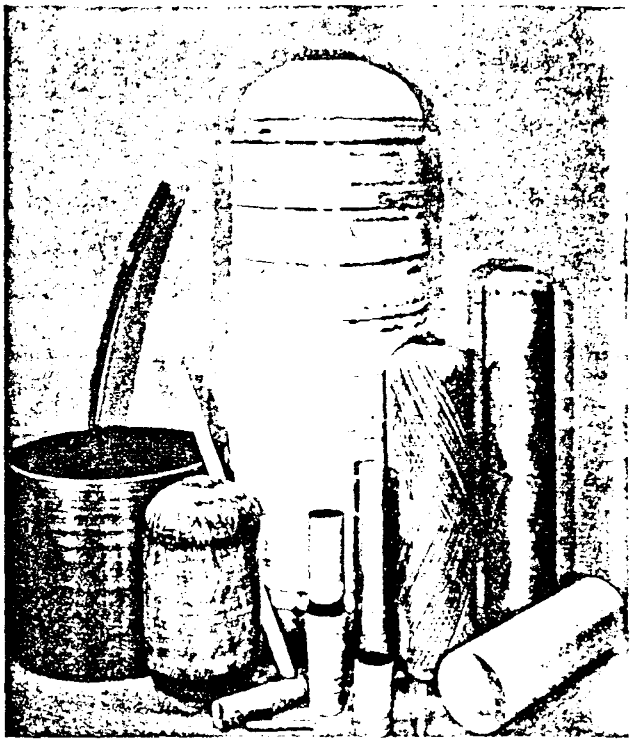
- Non-flammable. Used as jet nozzles for missiles, filament wound material is self-extinguishing.
- Non-conductive to electricity and heat. An ideal insulation, duct or conduit.
- Super-tough. Won't dent, bend, explode, distort, weather.
- Ideal for transporting and storing uncontaminated water, oils, liquids, grain, powders. F.D.A. approved resins are available.
- Functional and decorative as concrete forms, columns, beams, or light shields, in any color or translucent.
- Challenging. Engineering possibilities seem limitless. **Advanced Composites** materials may make it possible to use air pressure to erect and support exceptionally tall or heavy loaded structures. A whole maintenance-free marina could be built from it. Individual buried family shelters could be made safe and economically.

ADVANCED COMPOSITES

Nothing since the discovery of steel has brought such limitless scope to man's ability to engineer and construct old products better and new products economically.

ADVANCED COMPOSITES FILAMENT WOUND MATERIALS

Typical properties are listed below for composites using glass filaments and epoxy or polyester resins. Various properties may be adapted to your specification by changing wind angle, resin, glass filament ribbon width, and curing cycle.



CHEMICAL RESISTANCE — Below 140°F

	Polyester	Epoxy
WATER	E	E
SALTS	E	E
ALIPHATIC HYDROCARBONS	E	E
AROMATIC HYDROCARBONS	E	E
MINERAL OILS	E	E
VEGETABLE OILS	E	E
ORGANIC SOLVENTS	E	E
WEAK ACIDS	E	E
FATTY ACIDS	E	E
STRONG ACIDS	F	F
WEAK ALKALIS	F	E
STRONG ALKALIS	NR	G
OXIDIZING AGENTS	NR	NR

E - Excellent G - Good

F - Fair NR - Not Recommended

MECHANICAL & PHYSICAL PROPERTIES

HOOP TENSILE STRENGTH, PSI	180,000 to 230,000
AXIAL TENSILE STRENGTH, PSI	80,000 to 150,000
FLEXURAL STRENGTH, PSI	100,000 to 150,000
COMPRESSIVE STRENGTH, PSI	45,000 to 70,000
CROSS SHEAR STRENGTH, PSI	8,000 to 12,000
INTERLAMINAR SHEAR STRENGTH, PSI	3,000 to 6,000
FLEXURAL STRENGTH, PSI	100,000 to 150,000
MODULOUS OF ELASTICITY, (Tension) PSI	Up to 7×10^6
COMPRESSIVE MODULUS, PSI	Up to 6×10^6
MODULUS OF RIGIDITY, PSI	1.0×10^6 to 2.0×10^6
ELONGATION AT FAILURE (PERCENT)	1.6 to 3
HARDNESS, BARCOL	40 to 60
SPECIFIC GRAVITY	1.6 - 2.2
WATER ABSORPTION 24 Hour	0.1% - 0.5%
THERMAL CONDUCTIVITY: Btu/hr./sq. ft., °F/in.	2 - 6

ELECTRICAL PROPERTIES

DIELECTRIC STRENGTH	400-550 volts/mil
ARC RESISTANCE	150 - 180 seconds
DIELECTRIC CONSTANT:	
At 60 cycles	4.7
At 1,000,000 cycles	4.5
POWER FACTOR:	
At 60 cycles	85%
At 1,000,000 cycles	.0135-.0170
LOSS FACTOR:	
At 60 cycles	0.05
At 1,000,000 cycles	0.03
At 1,000,000,000 cycles	0.05 to 0.10

ADVANCED COMPOSITES has the most capable staff in the Western United States — competent in ALL reinforced plastic products.

Advanced Composites supplies filament wound products:

1. In spherical, cylindrical, conical, ellipsoid or ovaloid shapes
2. Which provide high strength to weight ratios
3. Will meet specific customer characteristics and tolerances (high performance, etc.)
4. Cost you less because filament wound parts have proven longer life than products manufactured from other materials — cost vs. performance therefore becomes a favorable factor.
5. **Advanced Composites** is in business to help you apply the advantages of these products to your uses.

USES OF FILAMENT WOUND PRODUCTS

To date, the majority of filament wound products have been manufactured to meet rigorous and highly specialized government and military needs, but the modern and highly automated methods of fabricating reinforced plastics has just begun to live up to its promise in the commercial areas. Filament wound storage tanks, oil pipes, ducts and pressure vessels are now being used in industry. The electrical industry employs filament wound switch gear, cable, conduit, high-voltage insulators, fuse tubes, battery casings, and other electrical components.

Other applications include railroad tank cars and truck tankers for transporting food and chemicals, water heaters and softeners, sewage pipe and irrigation pipe. The adaptation of filament winding to commercial uses has just begun. The possibilities are endless.

Materials Handbook
George Brady, '77

Carbon fibers are made by the Pittsburgh Coke & Chemicals Co. by pyrolyzing methane at temperatures to 1500°F and passing over a silica surface to yield masses of long and short fibers of 0.1- to 0.4-micron diameter. The carbon has a mesomorphic two-dimensional crystallite form, and the fibers are strong and flexible with a density of 1.991. Carbon fibers are produced as continuous filaments, 0.002 in. in diameter, with tensile strength of 200,000 psi.

Science News 122 (27 Nov. 1982): 343.

Benzene begets graphite fibers

In what may prove to be a major advance in materials science, Japanese researcher Morinobu Endo has "threaded" his way through a simple industrial chemical. Endo, of Shinshu University in Nagano, has prepared graphite fibers — carbon strands found in a variety of products, including heating pads and jet engine components — from benzene. Such fibers, to be marketed soon by the Tokyo-based Showa Denko Co., are both stronger and more flexible than those now available. This development in fiber technology was announced at the recent Materials Research Society meeting in Boston.

Graphite fibers now are manufactured from such parent materials as polyacrylonitrile (PAN) and rayon. The new fibers are expected to be not only better reinforcing agents, but also cheaper to manufacture than these PAN- or rayon-derived ones. The new strands are made in a process that involves heating benzene to about 1,100°C. At this temperature, the hydrogen leaves the benzene (C_6H_6), and the remaining carbon deposits on a metal catalyst in highly ordered strands that are typically about 50 centimeters long and 10 microns in diameter. Finally, the fibers are heat-treated: exposed to temperatures as high as 3,000°C that "purify," or remove most of the impurities in, the graphite.

Fibers produced in this fashion have been subjected to a variety of analyses by Endo and colleagues Trieu C. Chieu and Mildred S. Dresselhaus, both of the Massachusetts Institute of Technology in Cambridge, Mass. For example, the three researchers have studied the carbon fibers using Raman spectroscopy — a technique in which laser light of a specific frequency is allowed to shine through the material; the resulting scattered light is collected. The frequency of that light depends on the properties of the material being analyzed. In this case, Raman scattering has revealed that benzene-derived fibers "exhibit the highest degree of ordering" thus far achieved in such graphite strands, Endo and colleagues report in the Nov. 15 PHYSICAL REVIEW B. In other words, among the graphite fibers to date, the new ones come closest to being single, perfect crystals.

In fact, the benzene-derived graphite is so highly ordered that Endo and colleagues have been able to intercalate it — that is, insert between its layers sheets of a "guest" substance — with materials such as iron chloride. In so doing, they have developed a "synthetic metal" that is lighter than copper but that, in laboratory tests, shows comparable ability to conduct electricity. This syn-metal eventually could prove useful anywhere that lighter-weight circuitry is preferred — such as in the aerospace industry. *—L. Garmon*

Science Digest—June 1982

DENTPROOF CARS

In as little as five years from now, cars rolling off factory ramps may sport bodies made of a material that is virtually rustproof, heat resistant and, on minor impact, undentable. It is as strong as steel, yet so lightweight it would drastically improve fuel efficiency.

The "wonder material" is a composite of graphite (carbon) fibers incorporated in a matrix of plastic. It owes its strength to the unique properties of the fibers—low density and high tensile strength—and a couple of advantageous alignments. Within a fiber, molecules of carbon are oriented so that the strongest chemical bonds are lined up along its axis. The fibers themselves are embedded in the plastic in such a way that they internally mirror or reinforce the strength of the matrix. If all the fibers point in the same direction, maximum strength is achieved along the alignment.

Carbon-fiber composites have already gained popularity in the construction of sturdier airplane parts and virtually unbreakable skis and tennis rackets. Spurred on to design fuel-efficient, lightweight cars, the automotive industry, too, is keenly interested in them. The Ford Motor Company turned out an experimental model of a 1979 LTD that featured a body and chassis parts made with carbon fibers, and the lightweight car was found to provide just as comfortable a ride as its heavier counterpart.

Yet, hindered by one major drawback—cost—the future of carbon-fiber composites is not completely assured. Because the fibers are derived from such high-priced petroleum products as rayon or pitch, the material costs about $20 a pound, at least four times as much as steel.

The efforts of Teh Fu Yen, a professor of environmental and civil engineering at the University of Southern California, may soon change the situation. Yen is looking for cheaper ways to produce carbon fibers, and preliminary studies have suggested coal as a possible raw material. The composite could be made from asphaltene, a solid black waste product that results when coal is converted into a liquid fuel. Yen has found that not only can asphaltene form the matrix but it can also be heated to create graphite, in turn used to make the reinforcing fibers.

Says Yen, "From all lab observations, asphaltene works well. If scale-up procedures prove successful, the price of carbon-fiber composites could soon be competitive with that of steel."

Automotive Engineering, December 1981

Energy-absorbing structure improves aircraft safety

A recent study compared five types of lower fuselage structure for light aircraft in terms of their crash protection capabilities.

Five energy-absorbing lower fuselage structure concepts were developed for improving light aircraft occupant crash protection. They appear to be practical for incorporation into future metal airframes. Each was incorporated into a floor test section which featured a seat-supporting structure floor or platform with an energy-absorbing crush zone beneath, and subjected to static and dynamic tests. For most concepts, good results were obtained with control of loads to the structural floor, high energy absorption, and good structural integrity after impact. Those of lightest weight were found to be those efficiently using existing structure for energy absorption rather than using redundant, add-on materials such as foam. Further complete airframe tests are needed, as are parallel studies with composite materials whose failure mode differs significantly.

Accident prevention probably will continue to be the primary objective of general aviation manufacturers. However, even with intensive accident studies, technological developments, increased reliability, and improved pilot training, accidents may occur. To reduce risk of injury or death, design techniques are being investigated in a joint NASA/FAA program directed towards improving the survivability and crashworthiness of general aviation aircraft.

Crashworthiness is a complex subject involving human tolerance, crash environment (impact surface, terrain, aircraft velocities and attitudes), seats and restraints, cabin environment, post-crash fire, emergency egress, landing gear, and airframe structure. In addition, aircraft type will affect approaches to crashworthiness design. For example, to provide control of decelerative loads of seated occupants in a vertical impact, a different design approach would probably be used for a large transport aircraft compared with a light fixed-wing general aviation aircraft or a helicopter. The large transport fuselage, having considerable depth of crushable structure, may not require energy-absorbing landing gear and seats. On the other hand, light fixed-wing aircraft and helicopters having relatively little crushable airframe structure would require energy absorption in landing gear and seats as well as fuselage structure to prevent occupant injuries in potentially survivable crashes.

When designing a crashworthy airframe structure, many factors are considered. Of prime importance is design of the airframe to maintain structural integrity and a livable occupant space. Accident studies have shown that a protective structure around the occupant, along with adequate restraint, improves occupant crash protection in agricultural aerial application airplanes. The airframe structure should incorporate a high-strength protective shell or cage around its occupants. This structure should provide roll-over strength, a strong support structure for restraint of large mass items and seats, and maintain the integrity of normal exits for emergency egress. The forward fuselage structure should be designed to minimize plowing and to absorb energy during longitudinal impacts. In addition, crushable structure in an aircraft should be dual purpose, i. e., it should be designed to carry normal airframe loads as well as absorb as much energy as possible in a crash — otherwise a weight penalty will be paid. Also, structure which supports seats must maintain adequate strength throughout the crash to keep the seats from moving around. If the seat support structure is allowed to crush, it must maintain enough structural capability to support the seat loads. If the seats are energy-absorbing, the crushing structure must not interfere with the stroking seats.

While these studies deal with development of test floor sections, compatible with the NASA subsection, which would improve floor structural integrity and energy absorption of the fuselage in a crash, full scale testing of light fixed-wing aircraft is underway at NASA-Langley Research Center to study crashworthiness of airframe structures and seating systems. It was observed that, for some tests which resulted in high vertical floor loading, severe floor distortions and loss of integrity of the airframe structure occurred. To study the airframe structure more closely, NASA conducted drop tests of smaller fuselage subsections with loading from seats and dummies.

Description and philosophy

The study's main objective was development of crashworthy design concepts suitable for floor sections of light aircraft such as the twin-engine airplanes being tested at NASA. The NASA subsection's floor structure was used as a basis for design of these floor sections, and is shown in Fig. 1 with floor panels removed. The structure consists of twin longitudinal keel beams about 39 cm apart, with a depth of about 20 cm. Lateral bulkheads are spaced between 20 cm and 30.5 cm apart. There are two rows of seat tracks spaced about 28 cm apart.

Strengths of the floor and seat tracks were increased to be compatible with floor-mounted crashworthy seats which NASA was developing. Primary emphasis in designing the floor structure was ensuring that structural integrity was maintained so that seats and occupants would be retained and a protective shell would be provided

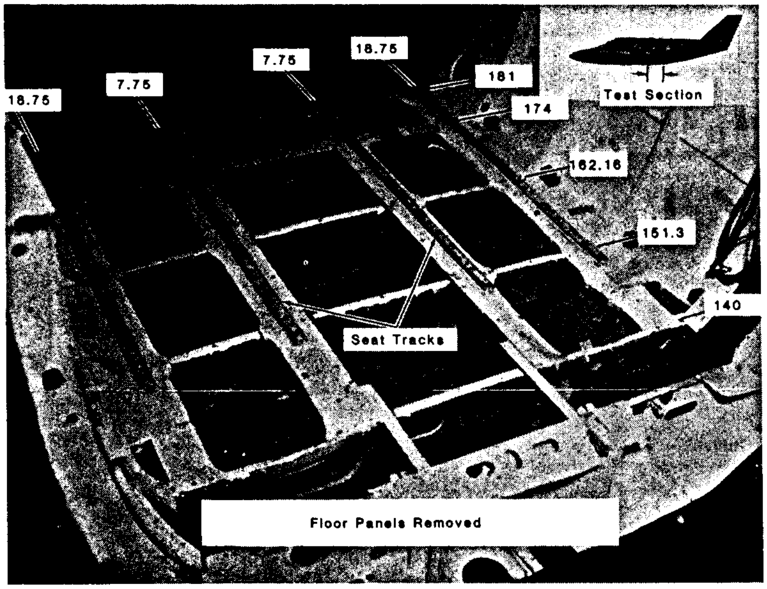


Fig. 1—Lower fuselage of NASA subsection is shown with floor panels removed.

in a crash. Floor damage with loss of structural integrity results in seats coming loose during a crash, subjecting occupants to secondary impact with the structure which often results in major injuries or fatalities. Note that a crashworthy seat and restraint cannot protect occupants from injuries if the airframe structure cannot retain the seats or if it collapses on the occupants.

The general design philosophy chosen for floor sections is shown in Fig. 2 and consists of a strong structural floor with a crush zone beneath. The structural floor is about 5 cm deep and strong enough to retain occupant seats without breaking up, heaving, or decreasing cabin volume. The energy-absorbing floor or crush zone is about 15 cm deep and tailored to control load application to the strong floor.

When designing the crush zone, it is important that the crushing load developed during a crash not exceed the structural capability, yet be sufficiently high so that maximum energy is absorbed. As seen in Fig. 2, a load-deflection curve for a conventional structure is generally characterized by a high peak load which will tend to heave up and destroy floor structural integrity. High peak load is followed by a sharp drop, normally after a stability failure; this results in low energy absorption (area under the load-deflection curve). On the other hand, an ideal crush zone would have a controlled peak load within the structural floor's capability and rectangular-shaped for maximum energy absorption as shown by the "controlled load concept" curve.

As noted, crash impact loads on occupants are controlled to within human tolerance by energy absorption in the seats, fuselage structure, and landing gear. Often, for aircraft impacts at highly oblique angle attitudes or on rough or soft terrain, the landing gear may fail, leaving fuselage structure and seat to absorb the kinetic energy and control the *g*-loads on the occupants. Since decelerative *g*-loads on occupants are inversely proportional to stopping distance, a reinforced structure designed to minimize structural deformations will result in increasing *g*-loads on the structure and occupants. Thus, the structure should be designed to have a zone which is intended to be crushed. This deformation should be restricted to areas outside the livable volume, and it should be controlled.

Although this work dealt mainly with future metal airframe designs, future airframes constructed of composite materials deserve special attention. When considering application of composites to a crashworthy airframe structure, it is known that these materials generally exhibit a characteristic low strain-to-failure behavior compared to metals. Ductile materials such as 2024 aluminum can tolerate rather large strains, deform plastically, and absorb considerable energy without fracture or separation. Because of this characteristic of composites, energy absorption will probably not come through an inherent stress-strain behavior as with metals, but rather through innovative design config-

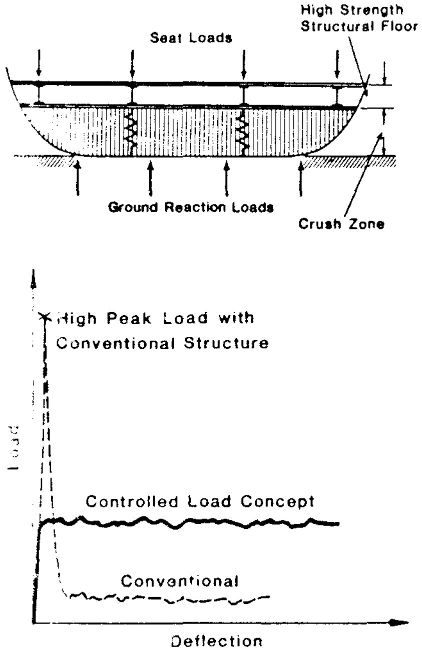
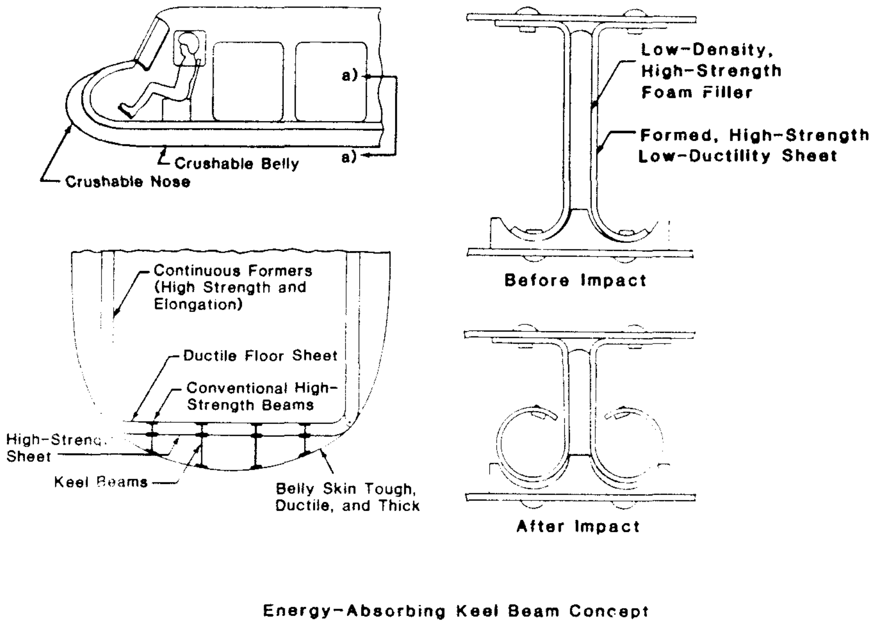


Fig. 2—**Design philosophy** for section in Fig. 1 is indicated both graphically and in terms of crush zone load-deflection characteristics.



a)
Crushable Belly
a)
Crushable Nose
Continuous Formers (High Strength and Elongation)
Ductile Floor Sheet
Conventional High-Strength Beams
High-Strength Sheet
Keel Beams
Belly Skin Tough, Ductile, and Thick
Low-Density, High-Strength Foam Filler
Formed, High-Strength Low-Ductility Sheet
Before Impact
After Impact
Energy-Absorbing Keel Beam Concept

Fig. 3—**Army helicopter concept** for energy-absorbing fuselage structure illustrates some details.

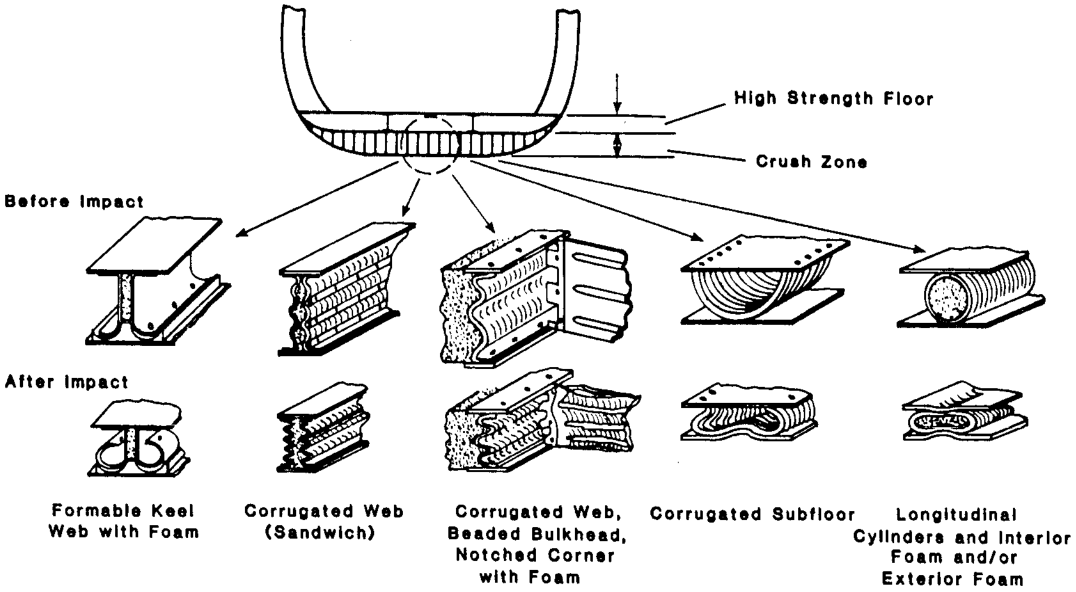

High Strength Floor
Crush Zone
Before Impact
After Impact
Formable Keel Web with Foam
Corrugated Web (Sandwich)
Corrugated Web, Beaded Bulkhead, Notched Corner with Foam
Corrugated Subfloor
Longitudinal Cylinders and Interior Foam and/or Exterior Foam

Fig. 4—Initial lower fuselage load-limiting, energy-absorbing concepts, left to right, are: formable keel web with foam; corrugated web (sandwich); corrugated web, beaded bulkhead, notched corner with foam; corrugated subfloor; and longitudinal cylinders plus interior foam and/or exterior foam.

urations. These will provide for energy absorption and force attenuation by other means; for example, the protective structural shell can be surrounded by a crushable material such as foam, honeycomb, or a crushable composite concept. The crushable material in the lower fuselage should be designed to attenuate crash forces, absorb and dissipate energy, and distribute loads to the stronger primary structural shell.

Energy-absorbing subfloor concepts

Several energy-absorbing crush zone concepts were considered in this investigation. A good example of such a design approach is presented in the Army Crash Survival Design Guide (Fig. 3). More conventional concepts such as honeycomb, foam, closed cells with orifices, etc. were also evaluated. However, material deformation concepts which utilized the existing structure required for flight and landing loads were considered the most attractive since redundant add-on weight would be minimized.

Besides energy absorption, there were several practical design considerations for the subfloor concepts. First, the concept should be multipurpose (used for airframe strength and stiffness as well as energy absorption) so that the weight penalty would be minimized. In addition, room for routing controls, wiring, and plumbing should be accommodated. Furthermore, the concept should perform well under combined loading with various pitch and roll attitudes at impact while maintaining a protective shell and reacting concentrated loads from seats and large masses. Finally, the concepts should be practical from a cost/productivity standpoint.

After reviewing available energy-absorbing concepts and considering their incorporation into a fuselage structure, five were selected initially. (Note that these were not the final five concepts that were fabricated.) From left to right in Fig. 4, they may be described as follows:

1 — *Formable keel web.* This absorbs energy by plastic forming of the keel beam web.

2 — *Corrugated sandwich web.* This absorbs energy by deforming preformed corrugated webs plus crushing of the foam filler.

3 — *Corrugated web/notched corners/foam.* This absorbs energy primarily by crushing foam, and has structurally tailored notched corners to reduce load spikes at the intersections of longitudinal keel beams and lateral bulkheads.

4 — *Corrugated half-shell.* This absorbs energy by bending deformation of a curved corrugated shell.

5 — *Foam-filled cylinder.* This absorbs energy by crushing foam with the cylinder walls needed primarily for web shear strength.

Note that many of these concepts used foam, which was later discarded because it was mostly add-on weight and relatively heavy compared with metal forming concepts.

For more subfloor concepts, design data such as load-deflection were unavailable so that design support testing was needed for further concept development.

Design support testing

Design data for the various energy-absorbing concepts were developed by static and dynamic compression testing to provide load-deflection data and evaluate loading rate effects. By varying some critical parameters such as thickness, geometry, bend radius, etc., a set of data could be generated from which a designer could size the energy absorber to give the desired stroking load. For floor sections, the desired stroking load was initially about 14.5 *g*'s, the vertical stroking load which has been widely accepted for attenuating seats. Note that in NASA's tests, the crush zone often exhibited considerably higher stroking load in the completed floor section, probably due to structure interaction and secondary structure effects which were ignored, such as lateral bulkheads (structurally tailored with cutouts), belly skins, and structure intersections. Therefore, larger design support test specimens should probably also have been tested, incorporating important structure interactions such as beam/bulkhead intersections and portions of bulkhead and skin.

Samples of load deflection data for the items of Fig. 4 are shown in Fig. 5.

1 — The formable keel web performed well, giving a flat rectangular load deflection curve for about 8 cm of a 13 cm length. The poor stroke-to-length ratio was due to the high density foam core used. Performance would have been much better had facesheets been thicker and the core material of lower density. This concept was eliminated, however, because webs could not be fastened with rivets and still be used structurally without creating too high an initial peak load.

2 — The corrugated keel web had an excellent performance both in load-deflection curve shape and stroke-to-length ratio. Its stroking load was relatively low compared with some other concepts, but, in combination with the required notched corners used for attaching keel beams and bulkheads, energy absorption was acceptable. Another advantage of this concept is that it can be used to carry structural loads while giving low compression loads, making it useful in tailoring with other concepts such as foam or notched corners.

3 — The notched corners concept was used to control the crushing load at beam/bulkhead intersections which can be extremely stiff and "spear" up through the structural floor if not properly designed. Notched angles serve as shear ties between keel beam webs and bulkhead webs while having low compression load capability. This concept was used extensively in conjunction with all concepts except the corrugated half-shell and the foam-filled cylinders.

4 — The corrugated half-shell concept exhibits good load control and energy absorption. It loses some efficiency initially by having a relatively low load and then develops a load spike at about 10 cm, at which point a fold on the sides of the shell bottoms out on

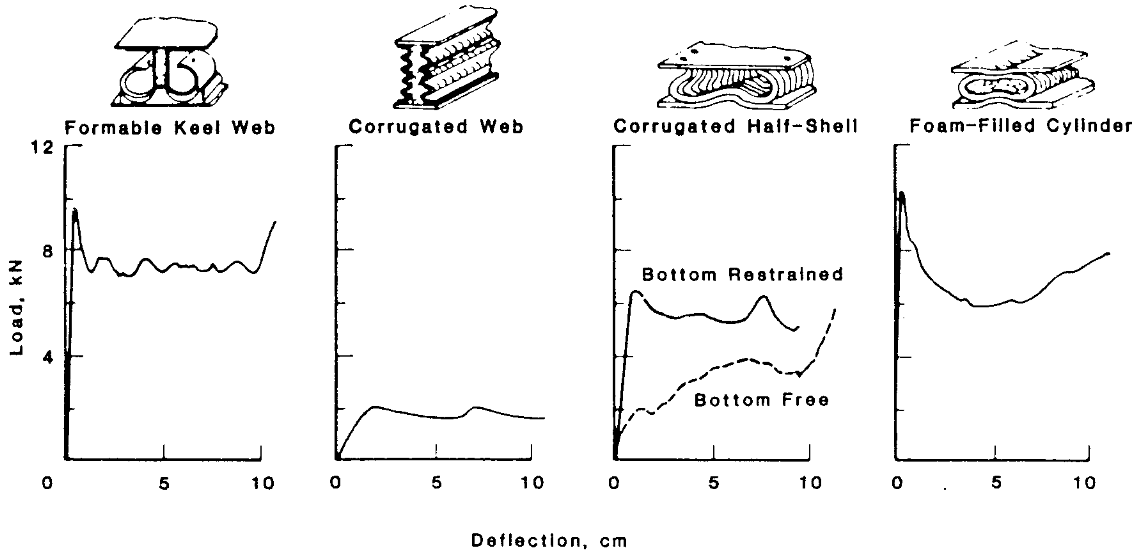
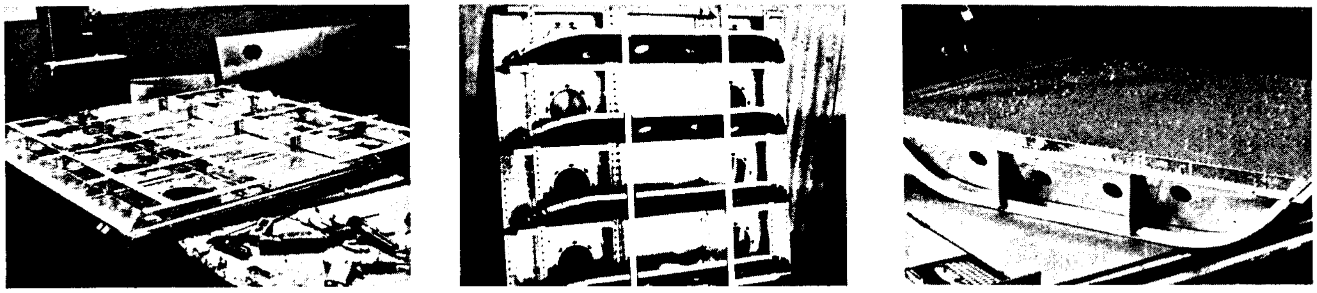


Fig. 5—Load-deflection curve samples for some of Fig. 4's constructions indicate relative performance.



a) Structural Floor (Upside Down)

b) Canted Bulkheads and Keel Beams (Belly Skin Removed)

c) Completed Section

Fig. 6—Fuselage floor test section assembly seen at various stages.

the test machine's lower surface. When the shell's bottom centerline is fastened down, the initial load is increased significantly, improving performance.

5 — Rigid polyvinyl chloride (PVC) foam was tested at both −54°C and at 74°C because of concerns that temperature would affect load-deflection characteristics. Temperature did not have much effect with low density foam. Energy absorption was good, with about an 80% stroke-to-length ratio before bottoming-out occurred. A 32 kg/m^3 (2 lb/ft^3) foam tested showed only about 15% increase in load under dynamic loading. However, higher density foams tested (56 kg/m^3 or 3.5 lb/ft^3 and higher) were highly rate sensitive.

Design & analysis of floor sections

Floor sections were designed using NASTRAN and KRASH computer programs, the former for sizing the structural floor to react seat loads and the latter to evaluate effects of dynamic loading of the seat on the structure for a vertical drop test condition. Results of design support testing were used to develop ground reaction loads for the KRASH analysis.

The seat used for floor section design was a floor-mounted, stroking seat being developed by NASA. The ground reaction load from the keel beam located under the inboard seat rail formed a couple with the seat reaction of the outboard rail, causing severe bending in the lateral floor member. If the lateral members were made continuous rather than the longitudinal, they would probably form plastic hinges at beam flange crippling locations, if overloaded, but remain continuous with good residual strength. This did occur with some sections during NASA's testing and was considered a good fail-safe design with adequate residual strength to retain the seats.

Crushable subfloor spring load-deflection data were developed from the design support test data. The KRASH results showed very high vertical g-loads on the occupant mass for a 9.1 m/sec (30 ft/sec) pure vertical drop test condition. (Normally, the seat should be designed to 14.5 g's vertical.) These high g-loads were due to design of the seat which was "tuned" for a 30° impact; thus, when impact was vertical, the vertical load factor was much higher because of the seat leg reaction loads. For a 30° aft impact, the seat would be practically rigid, with the load acting along the seat legs. However, the floor structure was still found adequate for a vertical drop since the forward static condition (longitudinal impact) put a more severe loading into the floor.

Final concept selection

Design goals for fuselage concepts were the following:

- Control crash impact loads and provide an integral structural floor which is needed for seat retention and to provide a protective shell around the occupied area
- Provide rectangular load-deflection characteristics for maximum energy absorption.
- Be lightweight and dual pur-

pose, i. e., serve as load-carrying structure under normal design conditions and provide occupant protection and energy absorption under crash impact conditions.

- Be inexpensive and practical for production.

After considering these goals, results of the design support testing, and application to an actual aircraft fuselage structure, the following concepts were selected to be incorporated into floor test sections and fabricated:

1 — Corrugated web with notched-corner intersections.
2 — Corrugated half-shell.
3 — Foam-filled cylinder.
4 — Notched corner intersections with conventional webs.
5 — Canted bulkheads with conventional intersections.

These last two concepts are considered minimum modifications to conventional structures while the first three are more unconventional.

Assembly procedure for one of the floor sections is shown in Fig. 6. Structural floor, belly skin, and contour were identical in all five section types. Features of each of the final five concepts are described below:

1 — The corrugated beam floor test section resembles conventional airframe structure with sheet metal skins, beams, frames, and stringers except for the configuration of the above-mentioned beams. The beam web material has been longitudinally corrugated to promote controlled collapse during the crush stroke. "Notched corner" or structurally tailored shear clips are also incorporated in this configuration (Fig. 7c).

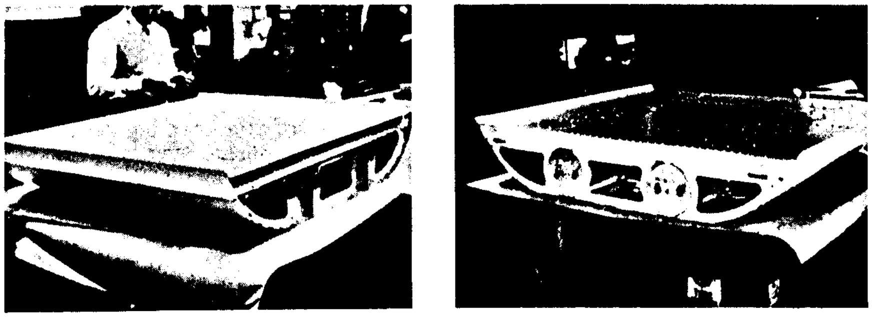
2 — The corrugated half-shell floor test section differs considerably from conventional structure. The primary fore-aft structural member resembles half of a large corrugated sewer pipe. It and outboard frames support the exterior belly skin (Fig. 7d).

3 — The foam-filled cylinder floor test section uses two longitudinal cylinders for primary fore-aft structure. Cylinders are filled with PVC foam material appropriately vented for absorbing energy. Cylinders and outboard frames support the exterior skin (Fig. 7b).

4 — The "mini-mod" notched corner floor test section incorporates conventional metal airframe structure with sheet metal skins, beams, frames, and stringers. Shear clips which tie beams to frame members have been structurally tailored to reduce their column stiffness and promote an accordian-style buckling mode for beams and frame members during the crush stroke (Fig. 8a).

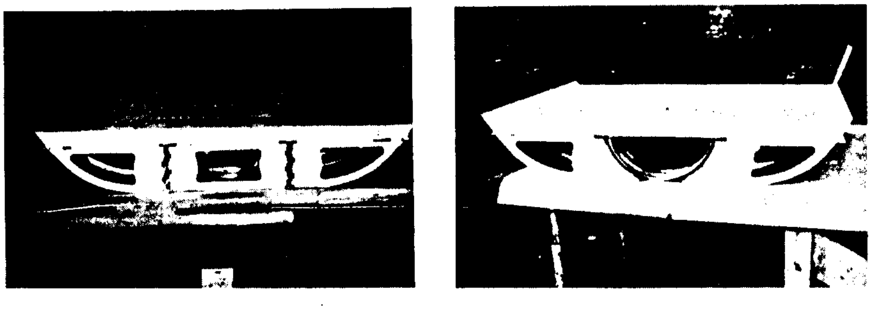
5 — The "mini-mod" canted bulkhead specimen incorporates conventional metal airframe structure with sheet metal skins, beams, frames, and stringers except that all frames are canted at an angle of 30° from vertical to promote their collapse during the crush stroke (Fig. 6c).

To obtain a relative comparison of the various concepts, comparable bulkhead and web size were used, based on strength requirements and what was observed in test sections at Langley. For example, lower bulkheads on all test sections were the same basic 0.64-mm sheet. Webs of all crashworthy



a) Notched Corners

b) Foam-Filled Cylinders

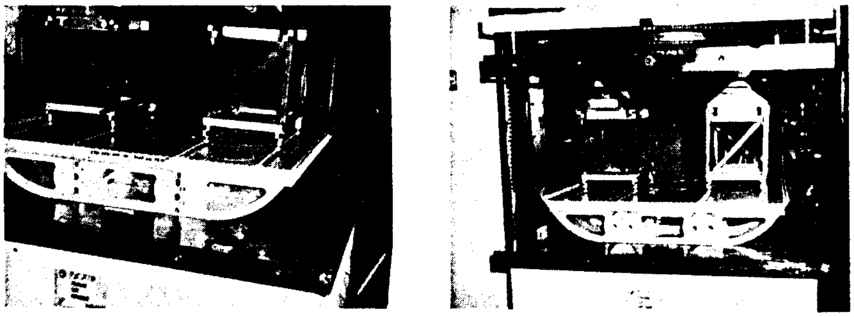


c) Corrugated Webs

d) Corrugated Half-Shell

Fig. 7—Completed fuselage floor test sections illustrate some differences.

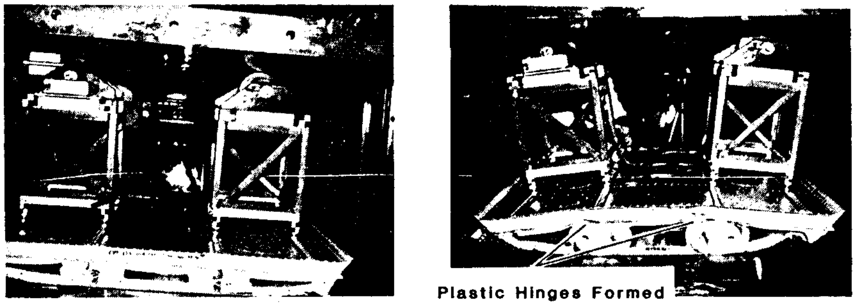
Before



a) Corrugated Web Concept

b) Foam-Filled Cylinders

After



Plastic Hinges Formed but Good Residual Strength

Fig. 8—Static tests of floor sections at NASA Langley indicate benefits of continuous lateral floor beams in avoiding plastic hinges. Floor distortion was not noticeable in dynamic testing.

concepts were 0.81 mm sheet except the foam-filled cylinders which have 0.51 mm skins. Shear clips or angles which include the notched corners tying keel webs to the bulkheads were all 0.81 mm sheet. Aluminum alloy 2024-T3 was the structural material throughout.

Final assembly weights for test sections were:

1 — Corrugated web — 16.1 kg
2 — Corrugated half-shell — 16.6 kg
3 — Foam-filled cylinder — 17.7 kg
4 — Notched corner — 15.7 kg
5 — Canted bulkhead — 15.9 kg.

The structural floor assembly and access panels for each section weighed 8.9 kg. It should be noted that screw and nut plates used on access panels added 1.1 kg to the section weight, which is not representative of lightweight aircraft construction. Note also that most concepts were relatively close to the same mass (within one kilogram) except for the foam-filled cylinder. This is because foam weight is strictly add-on, beyond that needed for structural purposes. The other concepts take advantage of structure required for basic strength, reconfigured to make it crushable. Weight penalty for adding crashworthiness features to all floor test sections except the foam-filled cylinder is estimated to average about 2.5 kg. For a 2724 kg airplane with a floor about three times the test sections' length, this would be a penalty of about 0.25% of aircraft gross weight. For the foam-filled cylinder concept, the penalty would approximately double.

Eighteen sections were fabricated with three or four sections of each of the five concepts and sent to NASA for static and dynamic tests. Some photographs of static test results are shown in Fig. 8. Note that the corrugated web concept performed excellently with no noticeable floor distortion, while the foam-filled cylinder concept had noticeable deformation of lateral members with plastic hinges formed above the cylinder locations. However, the structural floor for the foam-filled cylinder section remains intact with excellent residual strength for seat retention. This appears to support the design decision to use continuous lateral floor beams. Note that the foam-filled cylinder section had no noticeable floor distortion in NASA's dynamic test as it did in their static one. This is because the method of applying the static load introduces a lateral outboard load component to the seat which increases with increasing floor bending, so that once the floor starts bending, the applied load aggravates bending. For the dynamic drop test condition, however, the inertia loads developed on the seat mass give an inboard reaction load which acts to keep the seat upright. ☐

Based on SAE paper 810613, "Crashworthy Design Concepts for Airframe Structures of Light Aircraft," by **James D. Cronkhite,** Bell Helicopter Textron.